MPHIL

Improved Manufacturing Processes for Machining of Hard Metal Alloys in an SME

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Improved Manufacturing Processes for Machining of Hard Metal Alloys in an SME

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Declaration

I, Akbar Jamshidi, hereby state that all the work included in this thesis is my own. I confirm, to my knowledge, that it has not been submitted for assessment for academic or other purposes, and I verify that all work of others has been quoted and properly referenced to its original authors.

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Abstract

This thesis examines the implementation of an improved manufacturing information system for production engineering that was carried out over a period of 30 months within a Knowledge Transfer Partnership (KTP). The Department of Mechanical Engineering at the University of Bath collaborated with the Helander Precision Engineering Company in Tewkesbury.

The operations, manufacturing processes and information systems used by Helander are described together with a review of the hard metals used for the precise machining of industrial components manufactured from stainless steel, cobalt-based superalloys and nickel-based superalloys. The thesis contains a review of machining of hard alloys, statistical process control of machining and measurement systems analysis and an experimental study of the Inconel 718 superalloy is included which demonstrates how microstructure and mechanical hardness are affected by the machining process.

Methods of process control & process verification for manufacture including the use of gauge R&R are described to verify the accuracy of measurement tools. These methods are applied in two case studies which examine the manufacture of a simple part and a complex part. Helander's manufacturing processes are reviewed and practical methodologies are implemented for avoiding out of specification machined components. Improved accuracy in machining is achieved by the use of the Ballbar test to check accurate machine tool positioning. A future direction for Helander is additive layer manufacturing for net shape components and trials were undertaken by sub-contractors for Helander.

The KTP programme has made significant improvements in process control and understanding of hard to machine materials by integrating industrial and academic expertise in the field of precision engineering.

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Abbreviations

2D	Two Dimensions
3D	Three Dimensions
ALM	Additive Layer Manufacturing
APQP	Advanced Product Quality Planning
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BOM	Bill of Material
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAPA	Corrective And Preventive Actions
CIM	Computer Integrated Manufacturing
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
DLMS	Direct Metal Laser Sintering
ERP	Enterprise Resource Planning
FAIR	First Article Inspection Report
FCC	Face Cantered Cubic
FMEA	Failure Mode and Effect Analysis
Gauge R&R	Gauge Repeatability and Reproducibility
GD&T	Geometric Dimensioning and Tolerancing
IPI	Integrated Process Improvement
ISO	International Organization for Standardization
LIMA	Laboratory of Integrated Metrology Applications
MRP	Manufacturing Requirement Planning
MSA	Measurement Systems Analysis
NCR	Non Conformance Report
NPD	New Product Development
NPI	New Product Introduction

OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
PC	Process Control
PCP	Part/Process Control Plan
PDCA	Plan, Do, Action, Check
PDM	Product Data Management
PFMEA	Process Failure Mode and Effect Analysis
PLM	Product Lifecycle Management
PPAP	Production Part Approval Process
PSW	Production Submission Warrant
PV	Process Verifications
QCP	Quality Control Plan
RFQ	Request for Quotation
ROI	Return on Investment
SABRe	Supplier Advanced Business Relationship
SCM	Supply Chain Management
SME	Small and Medium Enterprises
SOP	Standard Operating Procedure
SRP	Supplier Requirement Procedure
SWOT	Strengths, Weaknesses, Opportunities and Threats
TQM	Total Quality Management
TQM	Total Quality Management
VMC	Vertical Machining Centre
VSM	Value Stream Mapping

Chapter One: Introduction

This research is concerned with optimising process control in the machining of hard metal alloys. It was made possible through a knowledge based partnership project between Helander Precision Engineering, the University of Bath and Innovate UK. This chapter includes an introductory background, objectives, the research question and finally the organisation of the thesis.

1.1 Background

The Laboratory of Integrated Metrology Applications (LIMA) at the University of Bath conducts research in metrology and provides independent R&D support for industry. Established in 2009 LIMA is an independent body for collaborative research and development of innovative metrology enabled applications. LIMA integrates fundamental research with industrial applications to develop new technologies which benefit UK Manufacturing.

The Helander precision engineering company was established in 1975 with the strong background in the turnkey supply of complex finished parts from difficult to machine hard metal alloys. The company provides design-for-manufacture consultation, raw materials provision and fully validated manufacturing with all required treatments and sub-processes. Parts are supplied to meet customer demand, supported by all necessary quality assurance validations. Helander specialises in high value manufacturing of parts for the oil and gas, aerospace and, more recently, nuclear industries. Parts are produced to high specifications and tolerances from difficult to machine metal alloys selected for their stability in oil and gas drilling environments. Helander's markets are classified into four main categories with bigger market in the first three listed below:

- Oil and Gas
- Aerospace

- Nuclear
- Defence

Until recently, Helander's main customers were in the oil and gas sector with two major customers being Schlumberger and Weatherford. However demand from customers in oil and gas industry decreased due to their recent price fall. In early 2016, only 50% of sales were in the oil and gas industry and the other 50% gone to aerospace, nuclear and defence industry respectively.

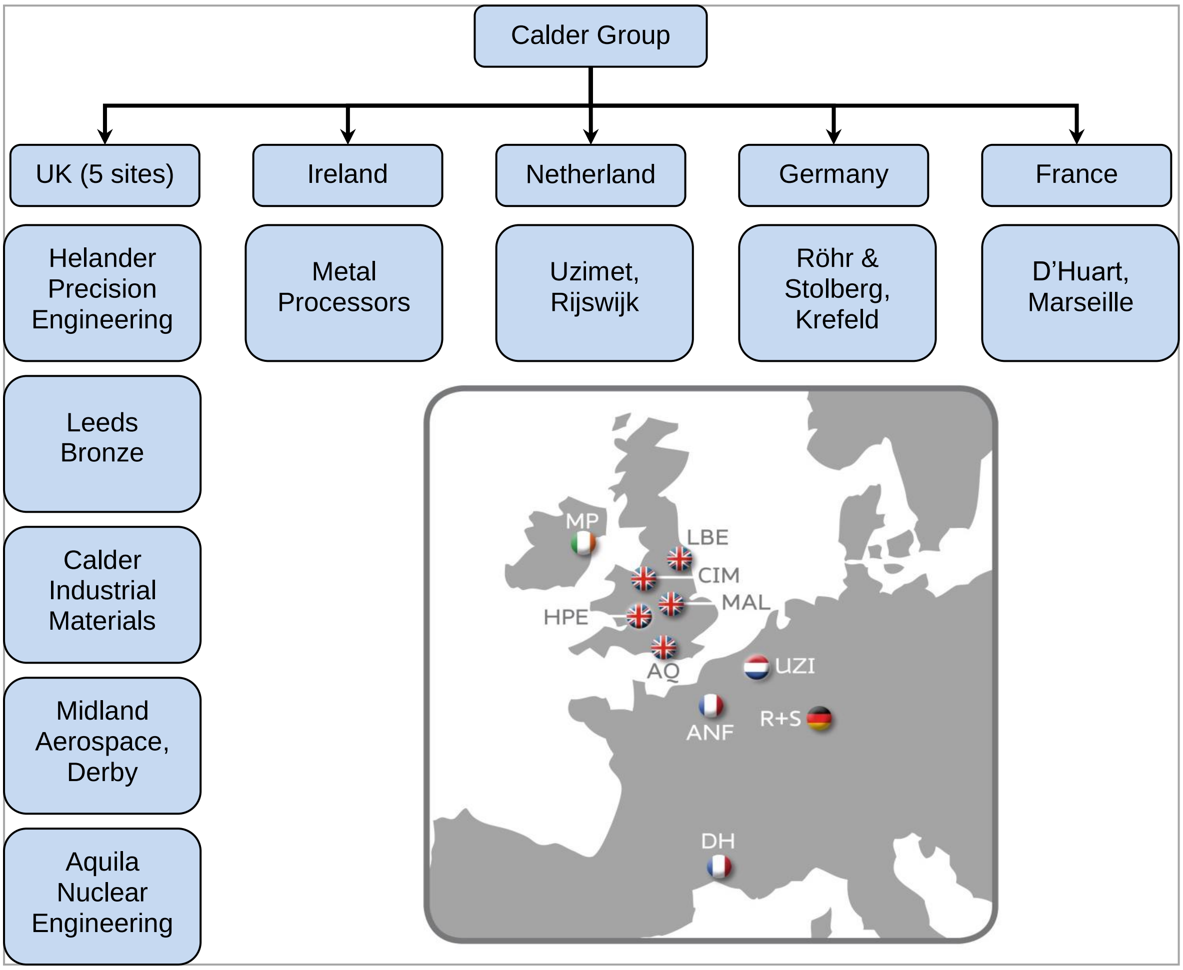

Figure 1-1 Calder Group locations

Since 2007, Helander has been a member of the Calder Group, a pan-European group with nine operating subsidiaries in five countries (Figure 1-1). The group supplies a world-wide customer-base in the aerospace, construction, healthcare, nuclear power, oil & gas and other markets. Calder group has great strength and stability allowing the challenges set by its customers to be met with matched investment.

The KTP project was introduced in the Helander company to enhance the existing process capability for long-term contracts with focus on excellent service and cost effectiveness. The goal was to develop a process and product verification system that complied with the requirements of upcoming industries as new customers. There are more than 35 SMEs working in the Helander supply chain. Products received and sent to these companies with different capabilities must be verified, based on different standard levels required and targeted by customers. The research reported in this thesis introduces a robust verification process that is aligned with Helander's capabilities and improves the confidence level in all stages of manufacturing operations. The aim is to impose systematic verification in Helander's supply chain to reduce variations in manufacturing components from batch to batch. These advances are in tune with the requirements of the nuclear, defence and aerospace industries which demand greater certification and documentation in comparison with conventional oil and gas customer.

1.2 Objectives

The aims of KTP project are:

i. To understand the needs of Helander customers which are mainly from the oil and gas sector (design intent, manufacturing process, onsite installation and maintenance).

   This section is explained in detail in chapter six and chapter seven. In chapter six the compliance and deviation matrix shows the oil and gas requirements and Helander's approach towards answering each need based on customer contractual requirement. Also in chapter seven, Helander's manufacturing process is explained in line with customer design intent and visual aids used in control plans to emphasise the customer's key characteristics.

ii. To understand and apply new methods and systems for design interpretation, measurement, machining and process verification.

   This section is explained in chapter six by introducing and implementing the FAIR (First Article Inspection Report) process with support of the IPI (Integrated Process Improvement) solution software to highlight and ensure the key customer characteristics are identified and appropriate solutions chosen for verification purpose.

iii. To work with customers within the supply chain to understand problems and future risks.

   In chapter six, details are given about visiting customers and discussing design procedures with customers. This is required to expand tolerances where possible and reduce risks in manufacturing procedures.

iv. To standardise the verification methodologies and convey the knowledge gained to existing production and quality staff by effective implementation of new design and process verification methods at Helander.

   In chapter six, two components were chosen as case study parts. The procedures from the early stage (quoting) until delivery of the parts were reviewed. Based on the reviewed components, it was identified which elements of the procedure needed modifying in order to reduce the cost and improve quality. The savings for each component were quantified and outlined. If the manufacturing method changes by using control plans and more accurate work instructions the benefits would be up to more than 5% of the revenue for the part in total.

These aims are in line with the objectives of MPhil which are:

i. A description of Helander including their operations, manufacturing processes and information systems, explained in detail in chapter two.

ii. A review of hard metals including stainless steel, cobalt-based superalloys and nickel-based superalloys. The review for each material group is provided in chapter three.

iii. A review of machining of hard alloys, statistical process control of machining and measurement systems analysis. Chapter four discusses this area as part of literature review.

iv. An experimental study of Inconel 718, reporting on microstructure and evaluating hardness as a function of distance from the machined surface. Chapter five describes the microstructural details for Inconel 718 in detail.

v. An investigation of methods of process control & process verification for manufacture including the use of Gauge R&R (Gauge Repeatability and Reproducibility) to verify the accuracy of measurement tools is shown in detail in chapter six. The Gauge R&R study results are presented in section three of chapter six.

vi. Two case studies of the manufacture of a simple part and a complex part. These parts are taken as examples for simple and complex part produced in Helander. Manufacturing procedures for each example were analysed in detail and savings are shown with new procedures being put in place.

vii. A practical study of Helander's manufacturing processes and methodologies for avoiding out of specification machined components. Manufacturing re-engineering procedure was proposed for this section from undertaking a review of the current process and introducing control plans and visual guides for critical areas of the components. This method aims to reduce the cost of quality substantially as most of the failures in production were repeated after few months due to not having a detailed and consistent process plan in place.

viii. An investigation of machine tool positioning including the use of the Ballbar testing is the context of chapter eight. The log system introduced and training performed for the Helander engineering team to perform the Ballbar test at regular time intervals in order to have confidence in the machines capability in manufacturing precise products to the machine standards.

ix. A description of additive layer manufacturing for net shape components and trials undertaken by sub-contractors for Helander. This is performed as development project for Helander's future products in chapter nine.

1.3 Research Question

Thus the research question can be formulated as follows:

"How can a new robust verification methodology be designed and implemented to give the Helander company a right first time manufacturing capability?"

1.4 Organisation of Thesis

This thesis has eleven chapters, including an introduction (chapter one) and conclusion (chapter eleven). Chapter two is an introduction to the KTP project company. Chapters three and four review the literature on manufacturing process and information systems, and materials and their manufacture at Helander, respectively. These chapters are generally for understanding what has been done so far and focuses on Helander alloys and manufacturing capabilities.

An in depth Helander material analysis and the impacts of machining process on the material microscopical structure and physical attribute are discussed in chapter five. In chapter Six two parts (simple and complex) are selected for detail analysis of time and cost savings and process improvements. The chapter also includes a gauge R&R study and reviews the process of manufacturing at Helander. Processes of manufacturing at Helander are reviewed in detail in chapter Seven and the processes are mapped at Helander as a whole company. In addition, cross functional diagrams are designed at Helander which describe the procedures that need to be followed according to the requirements of internal and external customers.

In chapter eight the process of machine performance and machine tool adjustment is described which is of critical importance for the quality and production. Chapter nine introduces the ALM process as not only a method for making prototypes but also for production and manufacturing with different alloys.

Finally, chapter ten is the general discussion and chapter eleven focuses on future work. The appendix section contains samples of forms and procedures for manufacturing that were designed and used at Helander company during the KTP project.

Chapter Two: Manufacturing Process & Information Systems at Helander

This chapter focuses on structure of the Helander company and the processes and systems that Helander is adopting to achieve lean manufacturing capabilities and to reduce uncertainties in measurement.

2.1 Company Structure

Helander Precision Engineering provides manufacturing services, specialising in high value machining of metal alloy parts for the oil & gas, aerospace and, lately, nuclear industries. Parts are produced to high specifications and tolerances from difficult to machine materials selected for their stability in oil and gas drilling environments. Helander has a good reputation for working with major oil & gas service companies due to long lasting collaboration with them. The components are typically made of corrosion resistant materials, which are hard to machine due to the high Nickel in their chemical composition and superior mechanical properties. This is due to rapid work hardening as a result of high-temperature and heat-resistant characteristic of these so called high performance alloy. (Figure 2-1) Subsequently, this makes it hard to control the related manufacturing processes.

To some extent, the company's layout reflects the need for different business sectors. Helander has four sites in Tewkesbury Business Park (Figure 2-2). Parts for oil and gas and aerospace industries which include more than 50% of Helander's sales are manufactured at sites 1, 2 and 4. Parts for the nuclear industry are only made at site 3 where non-contaminated tools and machines are allocated. There is a large degree of wasted time (more than an hour per day for specific operators)[1] and miscommunications happen due to company configurations and positions of the sites and machines. All parts except nuclear parts should be transferred to site 2 where

[1] This is including time to find the right person and the right required too and/or data from other site.

the inspection, wash and dispatch areas are located. This not only slows down the manufacturing procedures and wastes the energy of the company but also potentially damages the parts during transfer.

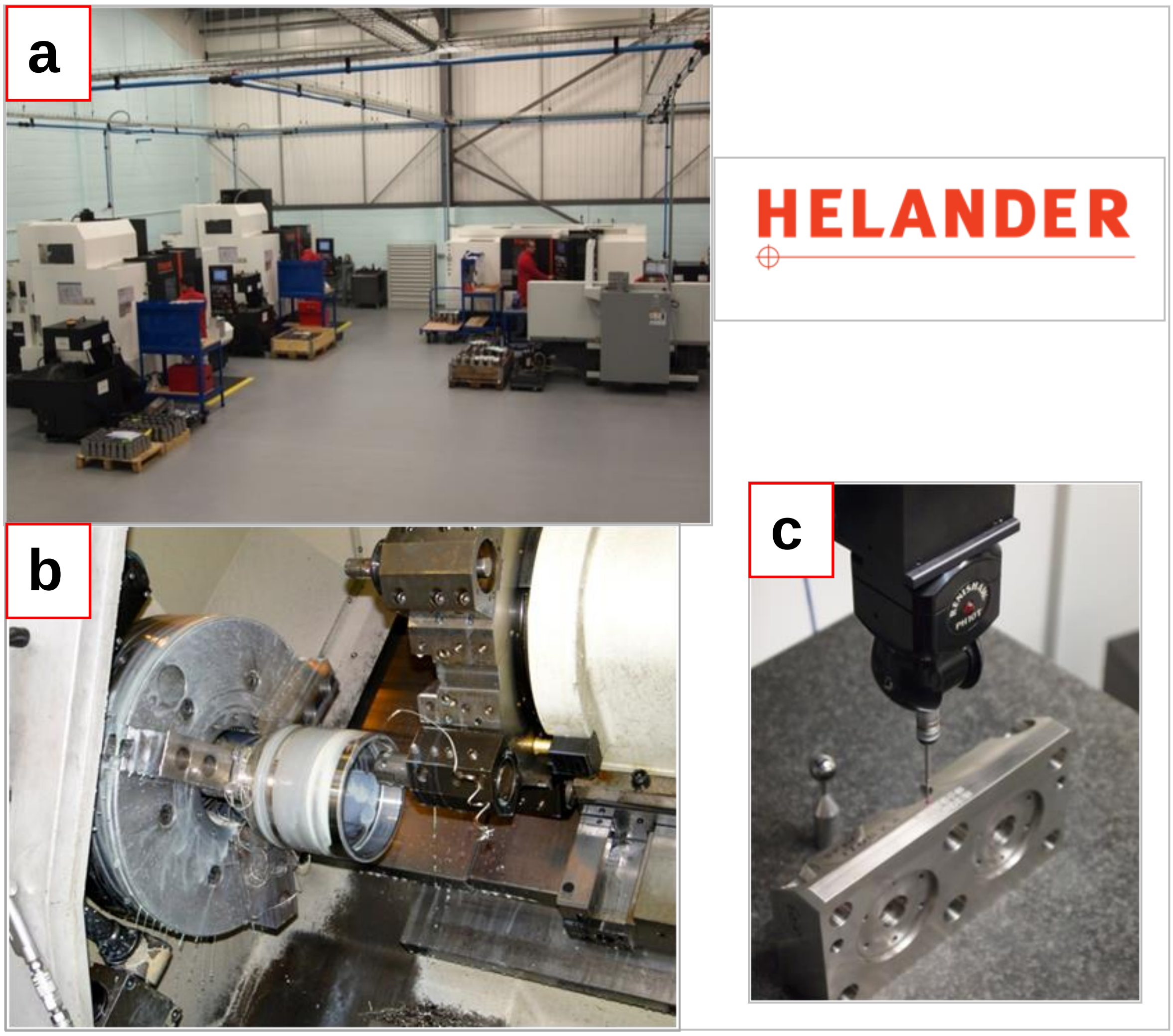

Figure 2-1 Helander company facilities
(a) CNC machines, (b) machined component, (c) touch probe verification

In January 2016 Helander had over than 180 employees which include an office based team and shop floor personnel who worked in three shifts. A list of Helanders' machinery and equipment is provided in Appendix 6.

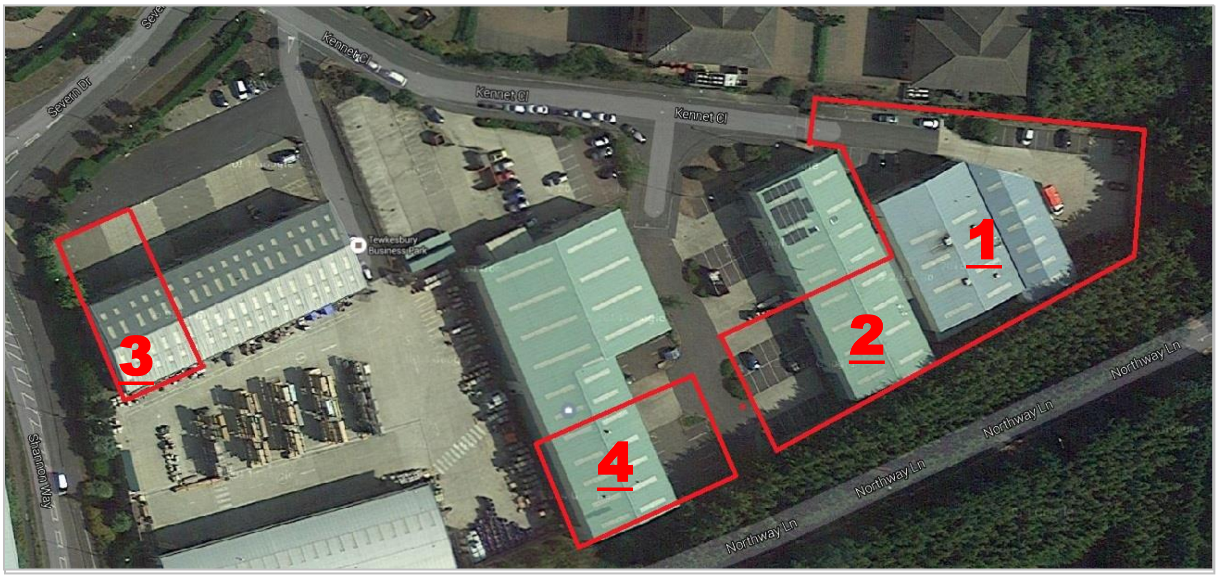

Figure 2-2 Helander company layout

2.2 Manufacturing Processes at Helander

Helander started as a small machine shop at the Tewkesbury Business Park in the 1970s. Helander's work across a variety of industrial sectors has been a catalyst for their engineers to adapt towards lean manufacturing methods. The philosophy of lean manufacturing is to eliminate waste in all aspects of the organisation. Waste comes in different forms, such as extra data, non-value added processes and, in more severe cases, wrong information due to changes in requirements and personnel as well as reduction in physical materials waste (e.g. out of tolerance machining and rejected parts). This waste feeds into production, which leads to use of inaccurate information and the manufacturing of non-conformance parts (Womack, 1990; Ohno, 1988; May, 2007). The introduction of lean manufacturing does not happening systematically and these changes are driven by necessity (i.e. ISO) rather than proactive process improvement. Necessities are products of non-conformances or errors in production, not genuine process re-engineering. In many cases, one of the motivations for process re-engineering is customer audits prior to placing an order. If a customer observes non-conformances (which is often the case for many SMEs including Helander), then they request an audit checklist which must identify a specific action plan for each procedure. This is a necessity if the customer requires the implementation of established procedures enshrined in documents such as ISO standards. In other scenarios, the frameworks imposed are often an exercise in paperwork (bureaucracy) designed to fit the purpose of the customer. In fact sustainable manufacturing and lean processes are implemented in the company in one way or another due to necessity. In reality, sustainable manufacturing operations need to include advanced and integrated aspects of verification to ensure all aspects of the product and the process are considered.

Bryan (1984) believes philosophy is an important factor in precision engineering that requires belief in the idea that the causes of variations in machine tools are the effect of incorrect processes in manufacturing. Incorrect processes can be understood and controlled. There is nothing random about the behaviour of a manufacturing process in precision engineering as long as the control plans are in-place to verify the products in different stages. Helander's philosophy has improved throughout their history through self-experience and sometimes closes collaborations with their customers. Every time customer requirements change under the framework of ISO 2001:2008 standard, Helander tries to adapt their process to satisfy customer demand. Helander's values have evolved by continuous improvement, elimination of non-productive procedures and investment in equipment. The current collaboration with academia (KTP Project) was the first of its kind where Helander chose to familiarise itself with different aspects of future market demand and to act accordingly in advance. These actions have determined Helander to work on its capability to manufacture parts for the nuclear and aerospace industry. Helander processes at the start of the KTP project were not adequate to respond to required documentation for nuclear and aerospace industries.

2.3 Order Process Systems at Helander

Upon receiving a Request for Quotation (RFQ), manufacturing businesses such as Helander should first identify key characteristics of a part to answer the questions "can we make it", "do we have the tools to make it" and "do we have a machine to make it on". There is also a question of adaptation and application in "design for manufacture" and "design for assembly". The initial challenge should be "what about measurement?" A significant number of manufacturing companies have the ability to make some very complex parts, however hardly any SME have the reasonable competence to correctly measure parts or measure within an acceptable range of uncertainty. Helander have a metrology department but their facilities were not utilised to the best of their ability at the start of this research.

Until recently, this issue was to a large extent ignored at Helander (evidence shown in section 6.3). Instead, a "Risk Analysis" marking section was designed in the form of a quotation sheet for estimators to indicate variability in terms of material, dimensions, delivery date. In brief, risk analysis on different orders (components) starts from the quoting process. The risk analysis is considered from the very beginning of the quotation review. As the orders are received at Helander, a Process Failure Mode and Effects Analysis (pFMEA) is applied to certain parts based on their complexities. This is in order to understand all the key elements of the part in detail and ensures they can meet the customer requirements based on Helander capabilities.

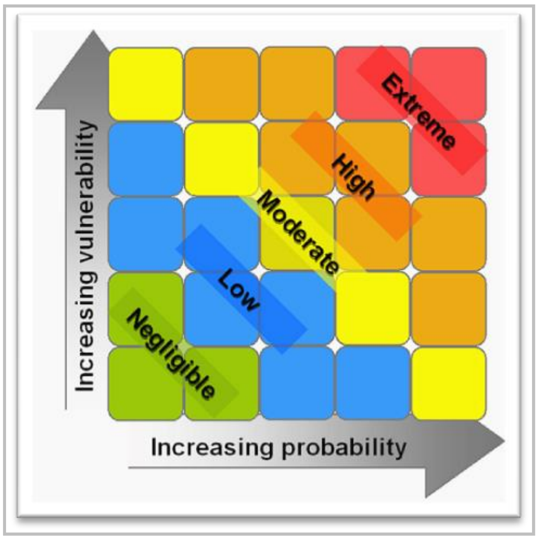

Figure 2-3 Risk register proposed at Helander to identify potential risks on orders (Speaker, 2014)

In many companies, the likelihood of potential failures and risks are ignored. The main reason could be the fact that manufacturing has evolved but understanding of it has not in the case of SMEs. Results of PFMEA along with risk factors such as part complexity, material cost, measurement method, tolerance and sub processes are considered to define the vulnerabilities of the project. Assessment can be made later on if any of these marks exceed a certain level (i.e. high/extreme) then a decision should be made by the engineering team to communicate with the customer in order to amend the design if necessary and to accept and/or reject the order based on its potential risk. Figure 2-3 shows that probability of failure and vulnerability of the projects are in the direct relationship. This principle used as a guideline to quoting team to consider the risks involved in projects.

Another factor which needs to be addressed at Helander is material variations in machining different alloys. Machinability will be affected by variations in composition and the nature of heat treatment which may cause these variations. To understand these variations test pieces of the same alloy are ordered and machining operations conducted with the same machining feed and speed. Also the same machine tools are used to find out which sample is easier to cut and what the causes of variations are from one alloy billet to another. Samples are also taken to the materials laboratory and prepared for microscopical analysis to observe the crystal structure and hence one of the causes of variation in machinability, explained in more detail in chapter 5.

On the inspection and measurement side of Helander, it was found that even after multiple verifications and inspections throughout manufacturing, occasionally parts shipped to customers were returned as rejects, mainly due to their dimensional non-conformities. Lack of knowledge in conventional manufacturing companies causes a tremendous amount of rework on products. These results increase cost, lead time and are responsible for capacity problems at Helander. Having the best MRP system in place in addition to advanced measurement systems is not helpful if companies are failing to assess their own capabilities in verification and manufacturing. Gauge R&R (Repeatability and Reproducibility) is an ideal tool for examining assessment programs that require subjective interpretation. Gauge R&R assists companies in understanding their own processes and validates the measured figures collected through the company's measurement systems. Gauge R&R brings more confidence to manufacturing processes and prevents rework caused by manufacturing out of specification parts. Results of the gauge R&R study are shown in detail in chapter 6.

Helander manufacturing system explained in brief with a short highlight on the problems right from receiving the order in the quoting procedure. The author tries to focus on the issue with regards to measurement and verification in the order review stage. This will reduce the risk to Helander while accepting each order. In order to have this process it is vital to have information support system that fully understood by engineering and inspection department with good knowledge about Helander supply chain.

Chapter Three: Literature Review of Metals & their Manufacturing

3.1 Introduction

Developments in the oil & gas, nuclear and aerospace industries demand materials with high performance and high temperature resistance under corrosive and oxidising environments. Helander's expertise lies in machining hard metal alloys which include stainless steels, cobalt-based superalloys and nickel-based superalloys. Superalloys were developed in the second half of the 20th century as high strength materials for use in severe environments. Superalloys are considered to be difficult-to-cut in machining operations. Furthermore, due to the precision required for superalloys applications such as aerospace industry, in many cases they must be manufactured with tight tolerances. This chapter describes the composition and properties of these alloys and challenges associated with machining them.

3.2 Stainless Steels

One of the most common materials used in metal fabrication is stainless steel. Stainless steel is used in a wide range of environments and applications due to its good machinability and anti-corrosive quality. In general terms, stainless steel is the name for group of iron-based metal alloys that contain 16-30% chromium. The chromium reacts with oxygen and forms an invisible barrier that protects the iron from corrosion. The barrier functions as a self-healing protection if the surface is damaged by abrasion, cutting, scratching or machining (Figure 3-1). However, as mentioned by Ryan et al. (2001), they are prone to pitting corrosion due to localised dissolution of the oxide coating in specific harsh environments.

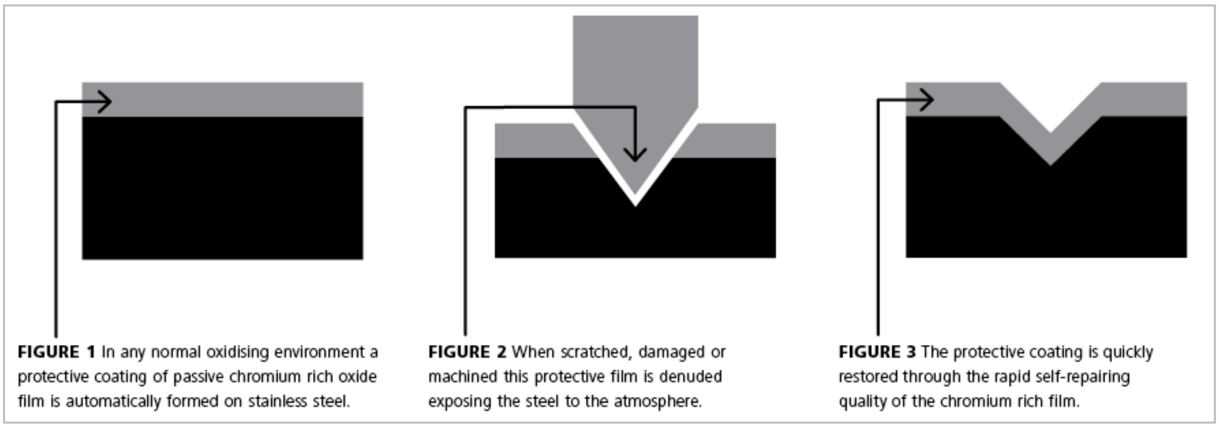

Figure 3-1 Self-healing process in stainless steel (ASSDA, 2015)

Unlike other groups of metal alloys, stainless steel is 100% recyclable. These metal alloys are highly formable and it is possible to make thin sheet material with consistent properties. Additionally, stainless steel has a moderately low melting point that makes it a suitable option for manufacturing by casting. Its durability makes it a popular alloy in many industries. Stainless steel can be nonmagnetic if annealed and hardened by cold work only (ASSDA, 2015). Stainless steel does not need protection, such as coating and painting, which makes it the first choice for a range of industries. Like other alloys previously discussed, there are five different groups of stainless steel described in Table 3-1.

Table 3-1 Groups of stainless steel (CES EduPack, 2015)

Group	Strength	Limitation	Applications
Ferritic	Cheap Good ductility Formable	Limited strength Poor performance in high temperature	Sea water applications, chemical manufacturing, cutlery, dishes, etc.
Austenitic	Excellent ductility Corrosion Resistance	Expensive Low yield strength High coefficient of thermal expansion	Exhaust parts, food processing equipment, heat exchanger parts, sinks, mining, oil refining, etc.
Martensitic	High hardness & strength Good ductility Moderate cost	Limited corrosion resistance Limited weld-ability	Pumps, valves, tools, turbine blades, food processing, marine, bolts and nuts, etc.
Duplex	Similar to Austenitic	Elongation is lower than Austenitic	Wastewater treatment, cooling coils, oil & gas and chemical industry, etc.
Precipitation Hardening	Very high strength Good corrosion resistance Good ductility Good toughness	Complicated heat treatment Expensive	Gears, fasteners, cutlery, aircraft and steam turbine parts, etc.

All of the Stainless Steel alloys are common at Helander except Duplex alloys that Helander has less order simply due to the customer preference. The chemical composition of a common Stainless Steel 17-4PH, is shown in Table 3-2.

Table 3-2 Selected chemical and mechanical properties of Stainless Steel 17-4 wrought - participation hardened (Adapted from CES EduPack, 2015)

Designation	Stainless Steel 17-4PH				
Condition	H1025 Solution Annealed: participations (age) hardened at 551°C, air cooled				
US name	UNS No S17400 ASTM S17400, ASTM 61				
Density	7790 – 7870 kg/m^3				
Composition %	C 0-0.07	Cr 15-17.5	Cu 3-5	Fe 69.9-78.8	Others Mn, Nb, Ni, P, S, Si, Ta
Young's modulus	197 – 207 GPa				
Yield Strength	1070 – 1110 MPa				
Tensile Strength	1100- 1180 MPa				
Hardness	250 – 460 HV				
Thermal Expansion Coefficient	12.5 – 13.1 µstrain/°C				

3.3 Cobalt-based superalloys

Cobalt-based superalloys are hard commercial alloys which are hardened by the use of carbides and solid solution hardening. Research by Devine and Wulff (1975) on cobalt-based alloys for implant applications has shown that the tensile and fatigue strengths of wrought cobalt chromium alloys were found to be more than double in comparison to cast alloys with the same chemical composition.

The cobalt-based alloys known as Stellite are suitable for applications in high temperature and highly corrosive environments (ASM International, 1990). Due to their popularity and wide range of use, Stellite has been widely researched. Cobalt-based alloys achieve their strength from solution hardening and other added elements in their chemical composition, such as tungsten and chromium. Nickel and carbon are also added to stabilise the high temperature form of cobalt alloys (Donachie, 1984). The chemical composition of a common cobalt alloy, Stellite 6, is shown in Table 3-3.

Table 3-3 Selected chemical and mechanical properties of Stellite 6 (Adapted from CES EduPack, 2015)

Designation	Cobalt-base Superalloy, Haynes Stellite 6k,				
Condition	Solution treated and aged				
US name	UNS No R0006 Haynes Stellite 6K, Haynes International Inc., USA				
Density	8300 – 8450 kg/m^3				
Composition %	Co 49-67	Cr 28-32	W 3.5-5.5	C 1.4-1.9	Others Ni, Fe, Si, Mn, Mo
Young's modulus	210 – 235 GPa				
Yield Strength	635 – 785 MPa				
Tensile Strength	1100- 1350 MPa				
Hardness	420 – 480 HV				
Thermal Expansion Coefficient	13.6 – 14 µstrain/°C				

These cobalt alloys are the most popular type for galling, corrosion, and wear resistance[2]. Stellite® 6 is graded for different industry applications. There are also various types of cooling methods used for casting Stellite® 6. Kuzucu, et al. (1997) measured harnesses of 40, 46 and 49 HRC for different cooling processes. The cooling methods were as follows: air temperature, cooling with water (2 hours), and cooling with liquid nitrogen (5 minutes). The chemical composition of Stellite 6 is shown in Table 3-4.

Table 3-4 Function of certain elements in Cobalt alloys (Adapted from Cobalt Facts, 2006)

	Nickel	**Chromium**	**Tungsten**	**Ti, Zr, Cb, Ta**	**Carbon**
Function	Stabiliser	Surface stability	Strength	Harms surface stability	Carbide penetration
Problems of extra use	Lower corrosion resistance	Forms TCP[3] Phase	Forms TCP phase	Harms surface stability	Decreases ductility

Stellite® 6 is suitable for oil & gas applications. It is appropriate for a range of hard facing processes and can be turned with ceramic and carbide tooling. Examples of its application in oil and gas industries include valves, pumps, drive shafts, and bearings. To retain high corrosion resistance, it is normally used with the same materials in the assembly parts (Delore Stellite, 2015).

[2] Commercially used at Helander
[3] Topologically Close Packed (TCP) phases is the cause to creep rupture properties and severely degradation in alloy

3.4 Nickel-based superalloys

Nickel based alloys, have unique features such as low thermal conductivity due to their high nickel content which causes a high surface temperature on the work-piece at the machining stage leading to deformation in the final product. Nickel based alloys may be classified into five main categories as shown in Table 3-5. For each category the mechanical and corrosion resistance can be enhanced by processes such as heat treatment, surface coating and shot peening depending on the application.

Table 3-5 Nickel based alloys (adapted from Udomphol, 2007)

Different types of nickel based alloys	Properties	Applications
Commercially pure nickel 95% Ni	• Good mechanical properties • Excellent resistance to most corrosive environment	• Food processing equipment • Electrical & electronic parts • Caustic handling equipment
Nickel-copper alloys (Monels) 67%Ni and 33%Cu	• High strength over a range of temperature • Good weldability • Excellent corrosion resistance	• Values, pumps, marine fixtures and fasteners • Chemical processing equipment. • Oil-well drill collars and instruments
Nickel-chromium alloys (Inconel 600, 601, 625) 30%Ni, 15.5%Cr, 8%Fe	• High corrosion resistance at high temperature • High strength and workability	• Heat exchanger tubing • Food processing equipment • Furnace muffle
Nickel-base superalloys (Inconel 718) 50% Ni, 18%Cr, 18% Fe, …	• Heat resistant and high strength at high temperature (760-980°C) • Good corrosion resistance • Good oxidation resistance	• Aircrafts, rocket engines • Industrial gas turbines • Nuclear reactors, submarines • Petrochemical equipment
Nickel-iron superalloys (Inconel 707, 718, 901) 25-45%Ni and 15-60%Fe	• High-strength of precipitation-hardened • Excellent mechanical properties for the intended service temperature	• High strength combined with ease of fabrication • Aerospace field, the alloy is used for turbine discs, shafts, and cases

In recent years, technology has moved forward in aerospace, nuclear, oil & gas industries at a great pace. However, limitations in the availability of metal alloys operating at high temperature with good strength and corrosion resistance is still an issue for the development of jet engines for aerospace and down-hole equipment for oil industries. Therefore the use of superalloys is very common in such industries. The most familiar superalloys for the oil & gas industry are the Inconel alloys 718 (UNS N07718/W.Nr. 2.4668). Some characteristics of Inconel 718 are shown in Table 3-6 (CES EduPack, 2015).

Table 3-6 Selected chemical and mechanical properties of Inconel 718 (adapted from CES EduPack, 2015)

Designation	Ni-Cr alloy: Inconel 718, STA						
Condition	Solution treated and aged						
US name	ASTM Grade: N07718; AMS: 5662, 5663, 5664, 5832, 5914, 5962, 5596, 5597, 5950						
Density	8180 – 8260 kg/m^3						
Composition %	Al 0.2-0.8	Cr 17-21	Fe 11-25	Mo 2.8-3.3	Nb 4.8-5.5	Ni 42- 64	Ti 0.65-1.2
Young’s modulus	198 – 208 GPa						
Yield Strength	1000 – 1110 MPa						
Tensile Strength	1170 – 1320 MPa						
Hardness	390 – 500 HV						
Thermal Expansion Coefficient	12.8 – 13.4 µstrain/°C						

Inconel 718 can be wrought or cast depending on the application. Cast superalloys may vary in grain size from piece to piece (Donachie and Donachie, 2012). Wrought superalloys were originally made by casting, followed by thermal and forming processes to reach their final form. In general, wrought superalloys are more uniform than cast superalloys. Most wrought nickel-superalloys are used up to 649 to 704°C. In most cases when temperatures exceed 540°C, steel and titanium alloys undergo corrosive degradation. Compared with other commercially available metals, superalloys are the most suitable metals for high temperature applications. In contrast with cast superalloys, wrought superalloys have a better ductility due to their greater uniformity and similar grain sizes.

At micro-structural level, Inconel 718 consists of an austenitic face centric cubic (FCC) matrix phase (γ) plus a variety of secondary phases. According to Thakur et al. (2008) chromium is the main element in Inconel 718, responsible for high temperature oxidization resistance which is the same as aluminium according to Matthew, (1984). The strength of Inconel 718 develops through solid solution hardening and precipitation (Figure 3-2). Sims et al. (1987) claim that gamma prime (γ′) phase aluminium and titanium are responsible for precipitation during heat treatment which strengthens the FCC matrix gamma phase.

The major phases present in the nickel base superalloys are as below (Heubner, 1998)

1. γ (gamma) phase – the continuous matrix of FCC austenite
2. γ' (gamma prime) phase – the major precipitate phase
3. Carbides – various types, mainly $M_{23}C_6$ and MC

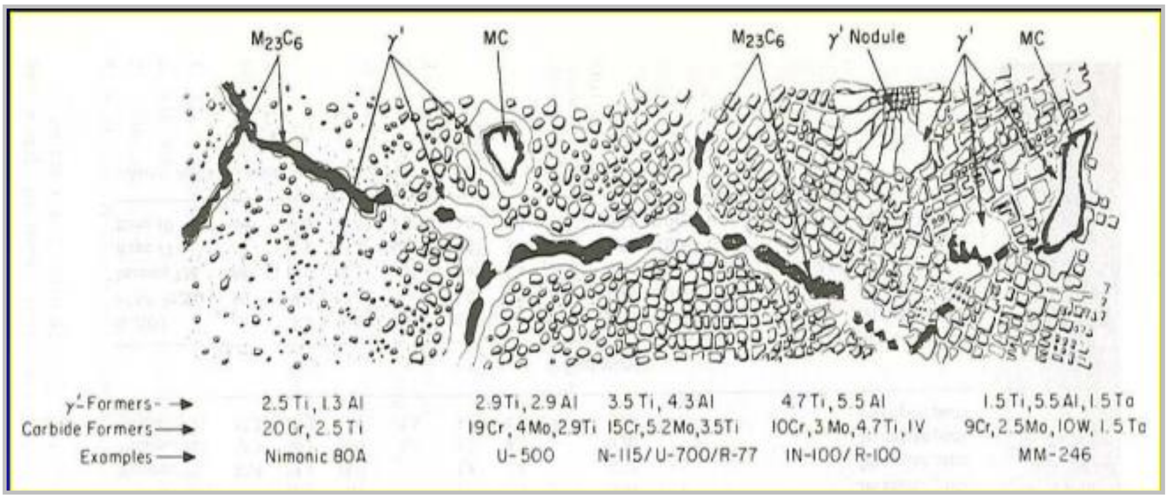

Figure 3-2 γ' (gamma prime) phase – the major precipitate phase (Heubner, 1998)

Different grades of nickel based superalloys are widely used in the oil & gas industry. Inconel 718 is also one of the main materials used in aerospace, due to its resistance to oxidation at high temperatures, and oil and gas, due to its corrosion resistance to gases containing a high proportion of CO_2 (McCoy et al. 2002). Due to their high hardness, machining consumes high amounts of energy, tool wear is high and machining takes more time. One of the major challenges is the variation in machinability which is caused by variations in the mechanical properties and microstructures in Inconel 718. It has been found that different sections of the same metal billet cut more easily in comparison to other areas due to deformations in the grain structures and age hardening caused by heat generation during machining. In many cases in dry and also while using coolant on machining due to the temperature rise (more than 1000°C in Inconel 718 alloy) in the contact area of the cutting tool and component the process of hardening happening which counts as a localised heat treatment of the material. This will harden the surface for the next cutting operation that can lead to sudden tool failure and breakages. Furthermore, heat and deformation generate cracks and micro structural changes that impact on the hardness of the material (Ezugwu and Tang, 1995).

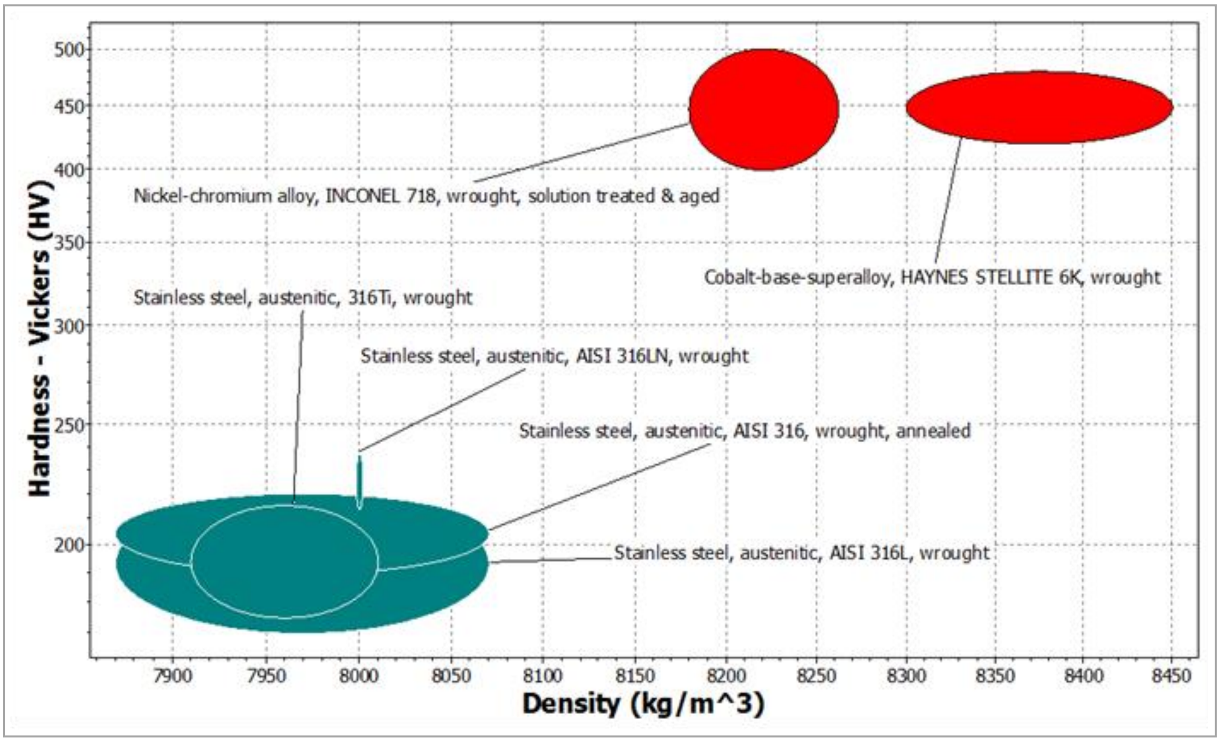

Figure 3-3 Hardness versus density for stainless steels and nickel-based and cobalt-based superalloys

The use of high speed machining is advised for such materials (Schulz and Moriwaki, 1992). The main benefits of high speed machining are lower cutting forces, reduction in lead time, elimination of heat with chip removal, ensuring less distortion and increasing part precision, and faster material removal rates, all of which result in lower energy consumption (Thakur et al. 2008). The outcome of these benefits can be seen in higher productivity and throughput (Schulz and Moriwaki, 1992). There is extensive research reported on machining superalloys (Thakur et al. 2008). Techniques involve different cutting speeds/angles, various cutting tools (carbide and ceramics both coated and uncoated) and choice of coolant materials (air and liquid). Despite all of this reported research there is little knowledge about these techniques within SMEs. A review on current journals in manufacturing reveals that most manufacturing companies are still working with outdated methods developed by their engineers internally and/or at best via consultation with their tool suppliers. The comparison between different types of stainless steel, Stellite and Inconel in terms of density and hardness are shown in Figure 3-3.

Chapter Four: Machining hard metal alloys – literature review

4.1 Challenges of machining hard metal alloys

Machining is generally the final stage of production at component level due to the accuracy in size and surface finish that can be achieved. It is also considered to be a costly process in manufacturing. In high value manufacturing, the machining process consists of selection of machining parameters, CNC part programming, design and use of different fixtures, the selection of various cutting tools and other detailed considerations regarding part inspection and machine tool utilization. Inconel 718 is considered to be one of the most popular materials for the oilfield industry. It is well-known for its challenges when it comes to machining due to material movement and hardening throughout the process. It has certain characteristics that make it popular for high temperature applications and it is widely used in gas turbine engines.

Material variations have a significant impact on machining quality. The main causes of variations originate from changes in chemical composition which affect mechanical properties such as hardness. The non-uniform distribution of metallic elements is a major source of variation in metallurgical structures. Different heat treatments are used to transform the material to the desired hardness levels based on application. For instance, in the case of Inconel 718 for drill string (assembled collection of the drill pipe) components in oilfield environment where high fatigue strength and high-corrosion resistance is required, a heat treatment protocol is used to develop fine grain size in the material. As Bhavsar et al. (2001) discuss, fatigue strength in Inconel 718 is highly affected by grain size. ASTM grain sizes 3 to size 5 are found to have optimum fatigue life and endurance[4] in corrosive environments.

[4] endurance limit is found to be greater than 60 ksi (414 MPa) on Inconel 718

Niemi (1971) reported that alloys strengthened by heat treatment (i.e. Inconel 718) are the most sensitive to micro structural changes. In order to achieve the required properties for Inconel 718, several standards for material specification are used commercially. One of the major standards is Aerospace Material Specifications (AMS) that specifies both the engineering materials and the fabrication process. The use of different standards is based on product specifications determined by the application. AMS 5662[5] and AMS 5663[6] are the most common heat treatment standards, which are also used in the oil & gas industry. AMS 5663 focuses on hardness and tensile properties at room temperature. The only difference between the two standards is that AMS 5662 requires solution heat treatment (Rockwell hardness about 20-25 HRC) whereas AMS 5663 requires heat treatment in addition to precipitation hardening (hardness about 36-44 HRC) (Wang, 2011). Precipitation hardening is the process that enhances the strength and hardness of the material by formation of very small uniformly dispersed particles of the second phase within the original matrix phase. Precipitation hardening is also called “age hardening” because the process develops over time below the solvus[7] temperature (Khaira, 2013). The study of different standards suggests that Inconel 718 can be heat treated to a lower hardness prior to the machining process. Therefore it is wiser to use AMS 5662 with less hardness, which facilitates lower machining force by comparison and increases the tool life, and then heat treat the components to AMS 5663 level. Research by Bhavsar et al. (2001) has shown the same results, that the alternative solution to reducing the machine cost is to use oilfield heat treatment which meets NACE (National Association of Corrosion Engineers) requirement (40 HRC max with 120-ksi (827 MPa) yield strength) rather than AMS 5663 (150-ksi (1,034 MPa) yield strength).

4.2 Machining Methods

Machining superalloys has always been a challenge due to the hard nature of the metal itself. Superalloys tend to harden during the machining process. The low thermal conductivity of superalloys builds up heat during machining operations (Figure 4-1, (a)) resulting in high temperatures at the cutting area. Research by Zhou et al. (2012) clearly shows that large deformation at the grain boundary is caused by

[5] AMS 5662 Solution Treatment: 1725°F - 1850°F + Air Cool
[6] ASM 5663 specification (solution heat treatment 1 hour in Ar at 950°C then air cooled, followed by precipitation heat treatment at 718°C for 8 hours, furnace cooled at 38°C/min. to 620°C held for 8 hours and finally air cooled)
[7] Solvus (temperature) is a line (binary system) or surface (ternary system) on a phase diagram which separates a homogeneous solid solution from other phases which may form by unstable or partial melting

dry machining and plastic deformation caused by generated heat. However, using coolant (Figure 4-1, (b)) helps to reduce the elongation effect with smaller plastic deformation.

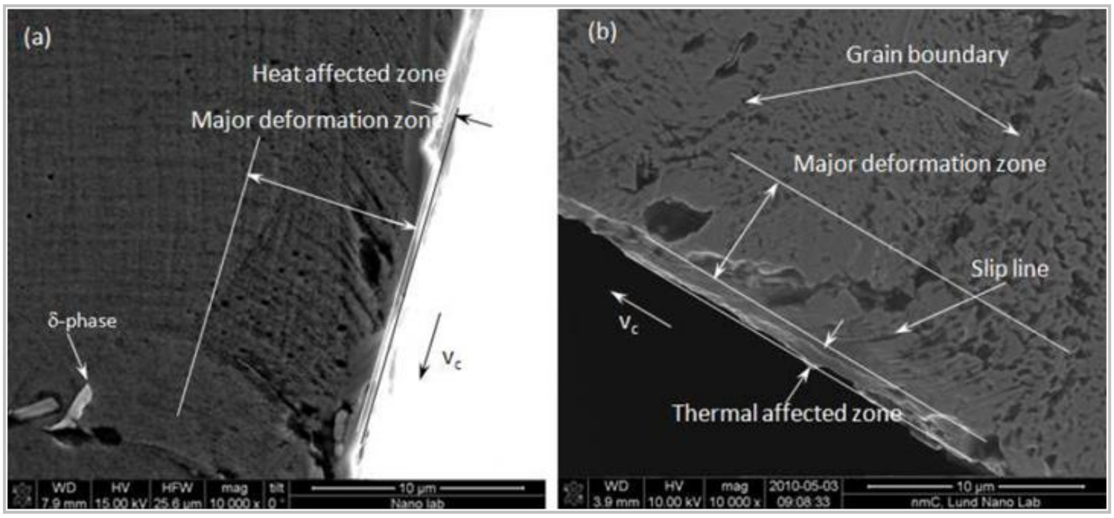

Figure 4-1Effect on the heat affected zone and of (a) dry machining and (b) use of coolant for a superalloy part (Zhou et al. 2012)

The high strength and toughness in addition to work hardening characteristics of superalloys demand a high cutting force (Liao et al. 2008). There are several research papers on machining superalloys by high speed turning (Pawade et al. 2008), use of round cutting edge tools (Fang and Wu, 2009), hybrid machining (Wang et al. 2003) and dry and high speed machining (Dudzinski et al. 2004). Each method has pros and cons, but there is still considerable work to be done to understand the nature of superalloys and to achieve a robust method for their effective machining. The more in depth review of key improvements in the machining of aerospace superalloys was published by Ezugwu (2005).

One of the major benefits of using high speed machining is the higher rate of productivity with a reduction in lead time and cost of manufacturing. Use of new tool also has a major impact on the quality of machined parts. Zhou et al. (2012) discussed the results of using a new tool (Figure 4-2, a) in comparison with a worn tool (Figure 4-2, c) to machine Inconel 718. The experiment was conducted with electron back scattered diffraction (EBSD) which determines the structure, crystal orientation and phase of materials in SEM. This information will allow an understanding of grain morphology and deformation in the specimens (Saoubi and Ryde, 2005). In the experiment the heat penetration that causes deformation is larger when parts are machined with a worn out tool on the machined surface (up to 50 μm thick). This can cause a dimensional instability in HVM (High Value Manufacture) parts. In contrast, the experiment with new tools at the same feeds and speeds shows the deformation zone concentrated in a very thin surface layer which is up to 10 μm thick (Figure 4-2, a).

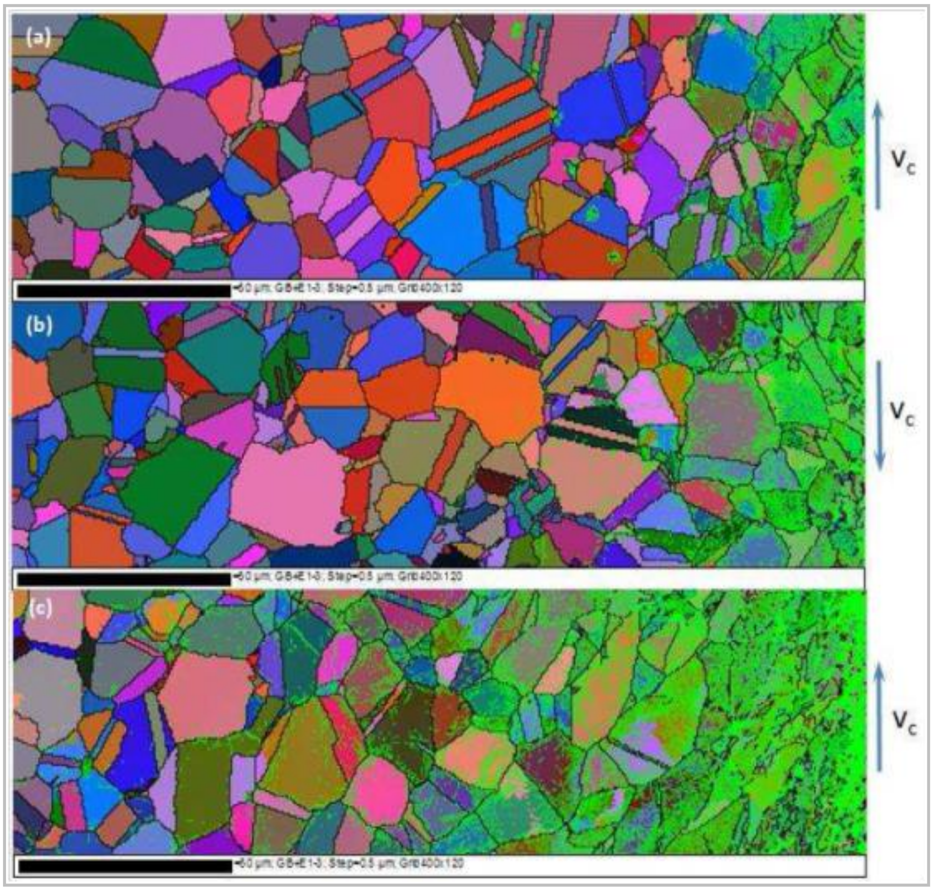

Figure 4-2 High resolution SEM images to determine the subsurface features of deformation using (a) new and (c) worn tools (Zhou et al. 2012)

El-Hofy's (2005) research reveals that the cut edge of the material is harder than the base material. He suggested that for rough turning and larger tolerances (for example: ±1.6mm) the impact of deformation is negligible because the final component dimensions have not been reached. For finish machining, when tighter tolerances are required, the new tool insert substantially decreases the surface deformation of the machined component. The new tool reduces the temperature of the work piece surface so there is less thermal shock on cooling which also decreases the possibility of crack formation on the surface.

Hybrid machining requires turning machines to be equipped with a heating source to make the component hot to facilitate machining and a cooling chamber to cool the tool in operation. Hybrid machining of Inconel 718 (Wang et al. 2003) using WG300 ceramic tools resulted in a better surface finish, longer tool life, and lower cutting force. A 50% reduction in cutting force led to a 156% improvement in tool life. Alternatively, cryogenically enhanced machining can be used, in which the temperature of the tool insert is kept low using liquid nitrogen to prevent the tool insert from overheating.

Another method for machining superalloys is laser assisted mechanical micro machining (Samanta 2012). This process generates heat from a laser beam focused on the work piece in the cutting zone. Cutting forces are reduced by as much as 30% compared to conventional machining. Lower cutting force can help to increase cutting speed with less tool wear.

Recently considerable research on cryogenic machining has appeared in the literature. Most of studies on cryogenic machining are on superalloys (titanium and nickel alloys). According to Shokrani et al. (2013) these alloys are chemically reactive to most tool materials. There is an ongoing argument on whether freezing the tool, the work piece and/or both of them would be more beneficial which is outside the scope of this research. Research have shown improved surface finish with a longer tool life in comparison to conventional dry machining; however the main drawback is high cost and low dimensional accuracy (Lu et al. 2013 and Wang et al. 2003). It is still hard to say which method for machining Inconel 718 is better as each method has its advantages and disadvantages (Table 4-1). Also variations in materials from different batches make metal machining easier in some cases and more difficult in other circumstances.

Table 4-1 Methods of machining superalloys (El-Hofy 2005, Lu et al. 2013, Shokrani et al. 2013)

Machining Techniques - Superalloys		
Technique	**Major Advantage**	**Major Disadvantage**
Dry machining (high speed)	High productivity rate	Poor surface finish
Hybrid machining	Good surface finish (no distortion)	High capital cost
Laser assisted machining	Low operating cost and short setup time	High equipment cost
Cryogenic machining	Higher cutting speed, better tool life and surface integrity, clean operation environment	High cost, dimensional inaccuracy

The major types of wear are abrasion, micro-chipping, surface deformation and built-up edge (BUE) on tools. Changes in dimensional instability occur, caused by residual stresses at microstructure level, depending on machining parameters (Subhas et al. 2000). Residual stress in machining is caused by non-uniform plastic deformation which is affected by thermal and micro-structural changes during chip removal and also interaction between the tool edge and work piece (Arunachalam et al. 2004). The other challenge in these alloys is the movement of the machined part due to material instability especially in superalloys (Ezugwu, 2005; Kitagawa et al. 1997).

4.3 Machining Parameters

In comparison to stainless steel, Inconel 718 has two major disadvantages. First, the cost of the alloy is much higher than stainless steel, and second, the machinability of Inconel is more challenging than stainless steel. Rashmi et al. (2001) claimed that in the use of carbide tooling, the feed and speed is 2 to 4 times less in Inconel 718 compared to austenitic stainless steel. Rashmi et al. (2001) suggest using oilfield standard (40 HRC) rather than AMS 5663 with heat treatment with 150 ksi (1,034 MPa) yield stress since the change in strength can significantly reduce the machining cost.

Inconel 718 has a high temperature capability and its resistance to creep make it a first choice for aerospace, oil & gas, and nuclear industries. However Inconel 718 tends to be influenced by work hardened effects in machining, resulting in strengthening of the work-piece material and further reduction in machineability. One of the main issues with Inconel 718 is material uniformity, which has a considerable impact on machining as two different batches from the same supplier can exhibit different machining characteristics. Due to the nature of high value manufacturing, which increases the use of tight dimensional tolerances, it is important to improve the control of the microstructure of superalloys. Mechanical energy to remove the metal in machining processes generates heat and plastic deformation. This heat usually alters the microstructure of the surface (up to 0.20 mm deep) to some degree and causes residual stress (Ezugwu and Tang, 1995). Plastic deformation and heat generation can lead to cracks at a microscopic level that may also cause dimensional instability and affect the structural integrity of manufactured parts (Arunachalam et al. 2004). High value manufacturing requires many stages of part verification at different levels from the very beginning of the process throughout all stages of component processing such as in and between machining operations.

Machining of superalloys is a challenging process because of the high strength of the metal and low thermal conductivity that leads to high cutting temperature up to 1200°C at the rake face. Dudzinski et al. (2004) explained that using high speed machining for Inconel 718 leads to lower cutting forces and higher removal rates and less energy in use. A comparison was made between K20 grade, CrN and TiN coated carbide tools with low and high speed machining of Inconel 718 at more than 50 m/min approximate cutting speed. The result of the study showed that the K20 grade lasted longer for cutting speeds in the range 20-30 m/min whereas coated carbides performed better at higher cutting speeds up to a maximum of 100 m/min due to high oxidization resistance, higher hardness and low thermal conductivity.

The temperature distribution in cutting tool has been of interest to researchers who have investigated the productivity of machining operations. There are various ways to measure the temperature while cutting different tool materials, which include tool chip analysis, hardness and microstructure changes in material, together with analysis of the cutting tool. Research by El-Wardany et al. (1995) on analysing the cutting tool (ceramic tools) describe that the use of FEA (Finite Element Analysis) and installing the thermocouple on the tool rake face as methods for measuring the temperature. The results for machining Inconel 718 with ceramic tools indicated that a speed of 510 m/min resulted in the minimum cutting-edge temperature. However, further investigation is required for machining this material at higher speeds.

These high temperature characteristics have a significant effect on the tool due to abrasion heat and pressure. The most common types of tool wear are shown in Figure 4-3. Among them are rapid flank wear due to abrasion, crater wear due to high feed and speed and tool notching due to work hardening effect which is typical in machining Inconel 718. In general tool wear rises as the temperature at the cutting edge rises. Each tool is designed to work at up to a certain temperature range. If tool is working below the designed range then the process is under-utilizing the tool and consequently the cycle time will be unnecessarily high. Above the temperature range the tool wear will be too high and consequently high tools costs and high machine downtime to keep replacing the tool. Conversely, high cutting speeds and temperature can results in poor surface finish and dimensional instability (Cadem, 2016).

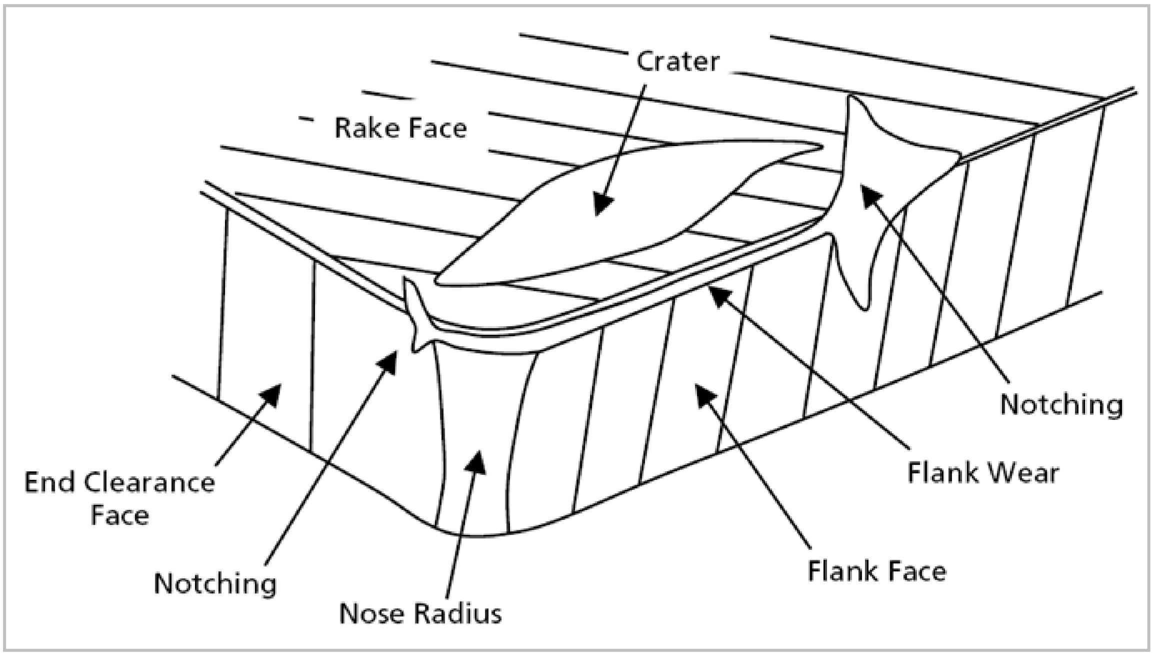

Figure 4-3 The most common tool wear in machining (Campbell, 2006)

Campbell (2006) instructions for machining superalloys as follows:

- Use positive rake angles to minimize work hardening and build-up edges.
- Use sharp cutting tools, help to minimize built-up edges and provide better surface finish.
- Use strong set-ups and prevent part deflection in order to, reduce vibration and chatter that can cause tool failures.
- Use high lead angles, spread the wear over a larger distance and help to prevent localized notching.
- When more than one pass is required, vary the depth of cut in order to spread the wear along the entire insert and thus prolong tool life.

4.4 Statistical Process Control (SPC) for machining metal alloys

The lack of expertise in the deployment of state of the art product and process verification techniques for machining is a quality and process improvement barrier for many SMEs. Resolving this problem requires a holistic approach towards the development of the manufacturing and inspection methods. The use of a Statistical Process Control (SPC) system is an important aspect of this approach. The SPC system helps to predict and control the variability when manufacturing a series of components. The SPC method is more complex and accurate than conventional methods of defining the instabilities in measurement such as interim measurement checks. The SPC method (which can be used on machine probes) verifies parts, draws a results line in a chart, and shows the trend between the minimum and maximum limit of the acceptance level (NPL guide, No 80, 2005).

Figure 4-4 shows how the process of checking conformance to a specification should be done by control processes in the form of an SPC chart. The chart contains a centre line, lower control limit and upper control limit. Every time that the measurement performs is computed from a sample of parts/products the control line collects the quality characteristic (in this case measured value). The control limit can be used to interpret whether the process is in a control zone. The record of data can also show if the variation is random or systematic. This approach is applicable to online and in-machine measurement probing that measures the key areas of the component right after the operation is completed. If the SPC chart shows a trend, it can be due to the defective measurement device or other elements of the manufacturing system are malfunctioning. Using SPC not only helps to predict the trend in manufacturing of parts but also minimises human error in measurement (Montgomery, 2009).

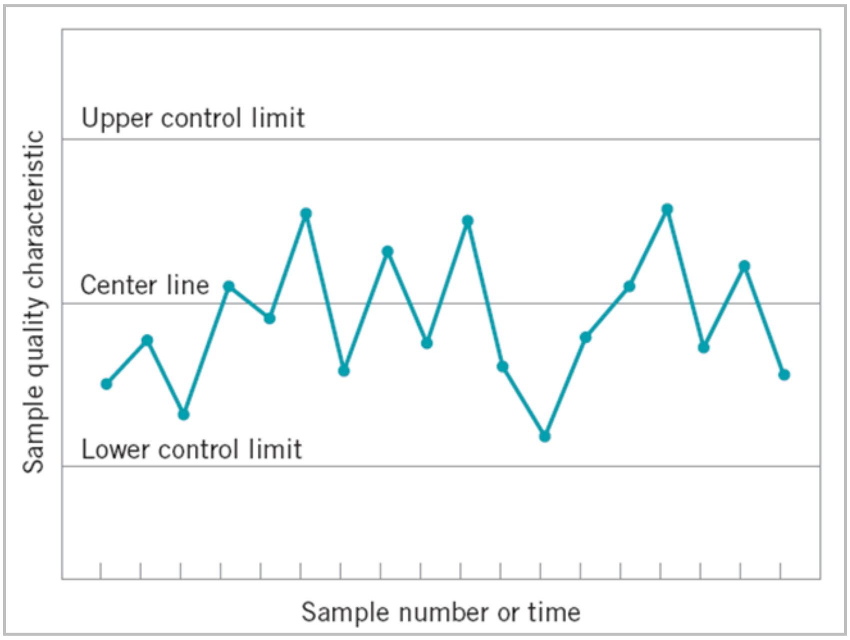

Figure 4-4 Statistical Process Control chart in a graphical display (Montgomery, 2009)

A graphical view of the control chart which reflects the results of the SPC system is shown in Figure 4-5 which defines machining limits for design against manufacturing.

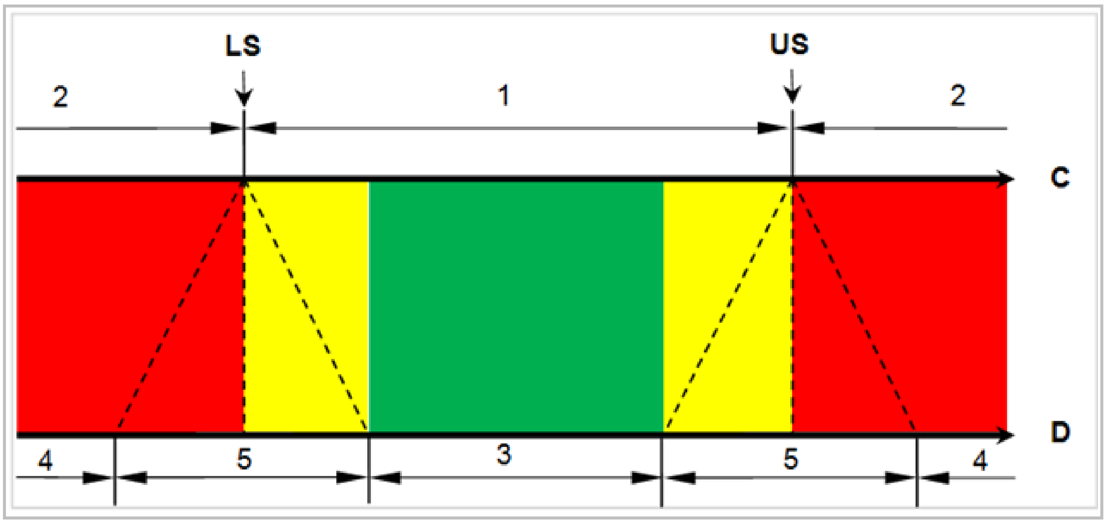

Figure 4-5 Control chart which defines machining limits for design against manufacturing (Courtesy of NPL guide, No 80, 2005) LS = lower specification, US = upper specification

The real world is different to the design world when it comes to measurements. As shown in Figure 4-5, line C illustrates the design specification (data from CAD model and drawing) and line D illustrates the physical measurement following verification. From the point of view of the designer, the region labelled No 1 is the zone of conformance specified by designers and the region labelled 2 is the non-conformance zone. In terms of real life physical measurement, zone 3 is the optimum range of acceptable machining and zone 4 is completely out of tolerance. The problem is that in the real manufacturing world, no absolute boundaries exist to separate the LS (lower specification) and US (upper specification) limits. (The LS and US are determined as part of the design and functionality of the component. Instead, there is a grey area (shown with No. 5) known as the uncertainty range which limits the area of conformance by designers to an area of conformance by manufacturers. This area of uncertainty in the best case scenario illustrates that there is a 50% chance that the measured figure is in the acceptance area. As shown, half of the area No. 5 is in the design acceptance zone (yellow) and the other half shown in "red" is in the non-conformance zone. The aim of the SPC in manufacturing is to show the direction and range of measured parts and notify the operator when the process will go out of the "green zone" and into the "yellow zone". This gives the operator a chance to perform corrective and preventative actions (CAPAs) and redirect the control line into zone 3, the "green zone" (NPL guide, No. 80, 2005).

Using the SPC system enables manufacturing operators to verify all parts on the machine fixture and show where the trend is. This process is part of integrating inspection into the manufacturing process. It is predictable that processes may be out of control, due to changes in tool, temperature, material or environment. The fact is that the SPC trends might show parts are in control after a certain degree of verification, but Flack and Hannaford (2005) stated the combination of variations in the manufacturing environment constantly divert the trend line to the out of control zone. Therefore the CAPA principle should be always in place to monitor the process. Tubiak and Benbow (2009) categorised processes into four states:

- 100% conformance
- Random state (unpredictable)
- Occasional state
- Occasional random state

As shown in Figure 4-6 the control level has a direct relationship with conformance level and by nature the processes shift to the lower control level.

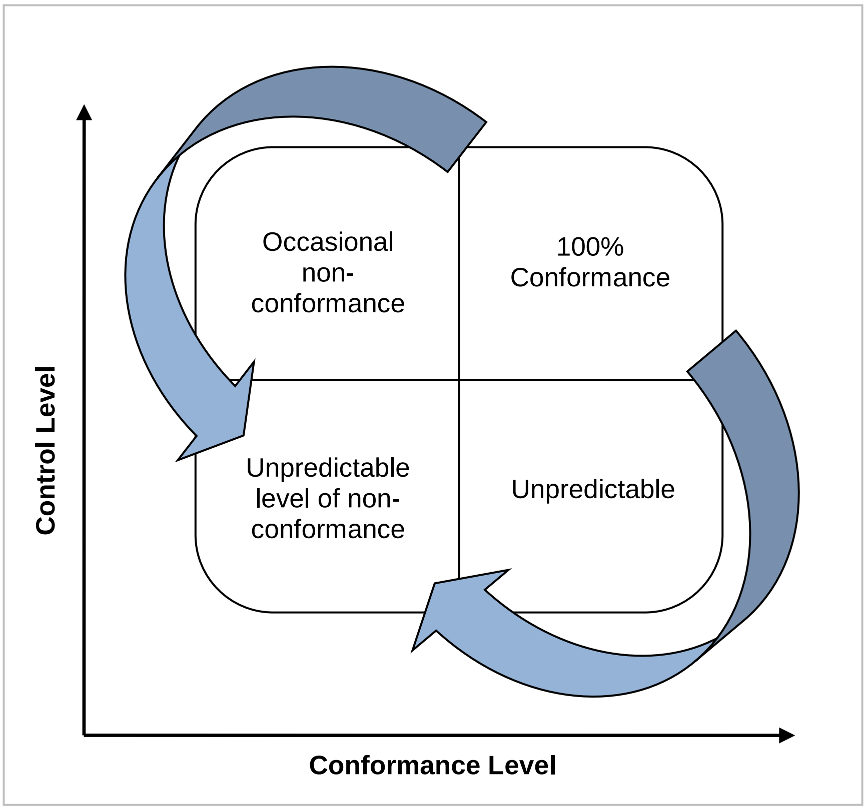

Figure 4-6 Four process states (adapted from Tubiak and Benbow, 2009)

The SPC system and its trend movements can show when the process starts to divert and give a warning that at least one element needs to be addressed in order to bring the process back in control. The SPC system can be used in on-line inspection, process control and tool set up, and can predict and reduce the probability of manufacturing defective parts.

There is a knowledge gap in utilising online measurement systems on production machines for inspection purposes in order to have an integrated verification process. The benefit of using the SPC system is that it is possible to verify the components while they are still on the machine rather than after they have been dismounted and moved to the inspection area. This saves operational time on the shop-floor by not taking parts to measure manually and reduces the workload of the inspection department (Kumar and Newman, 2009). Some parts will always require much greater inspection, using devices such as CMM (coordinate measurement machine). The SPC system with the use of probe measurement may not be applicable to these devices for verification purposes in manufacturing. This is due to the capabilities of probe measurements that is firstly less than the CMM and secondly are not in the controlled environment such as metrology laboratory.

4.5 Measurement system analysis

Measurement system analysis (MSA) is a way to define the accuracy of measurement. MSA provides decision makers with a useful set of tools for understanding which parts of a system causes the highest variation (Murphy et al. 2009). It determines how much of the variations within the measurement process contribute to overall process variations. These variations can be linked directly to the true dimension of the part, the skill of the operator and the measurement device. The practice of gauge R&R (Repeatability and Reproducibility) identifies problems in measurement systems. Measurements come with variations that are themselves the result of variations in the environmental conditions such as temperature, humidity, vibration and radiation. Reducing variations with an automated machine probe system can help to avoid defects in future products. This is due to the risk of damaging the parts in variation of procedures. Gauge R&R helps to identify which part of the measurement system makes the greatest contribution to possible error value. Gauge R&R also checks whether the performance of the measurement system is recognized over time and whether it is going to change within a range of parts. It is necessary to evaluate variations in a measurement system before investing in measuring devices. Accuracy and precision values can be achieved at the same time using gauge R&R practices.

MSA encompasses the complete process used to obtain measurement such as the collection of instruments or gauges, standards, operations, methods, fixtures, software, personnel, environment and assumptions used to quantify a unit of measurement. Other elements that can be part of MSA include any fixed assessment to the feature characteristic that is measured. The usefulness of MSA was shown earlier in the SPC explanation and will also be shown later in chapter 6, where the application of MSA is presented in a measurement case study. A schematic view of measurement systems variability is visualised by AIAG (2010) in a cause and effect diagram (Figure 4-7) that highlights the variations which exist under each category (work-piece, standard, environment, people and the measurement instrument). The assessment of the variations in the measured value can be the result of random error. The causes of errors are sometimes difficult to determine due a wide range of inputs in the measurement system. For example, the error could be due to linearity, uniformity, repeatability, or reproducibility of certain elements or combination of different elements or their effect on other factors. Other examples can be errors in the CMM machine due to the effect of temperature on the linearity of the CMM machine axis. Some of these errors can be mitigated by using troubleshooting manuals from manufacturer; however there might be a need from experts to re-adjust the machine. Controlling these causes will add stability and consistency to the measurement system.

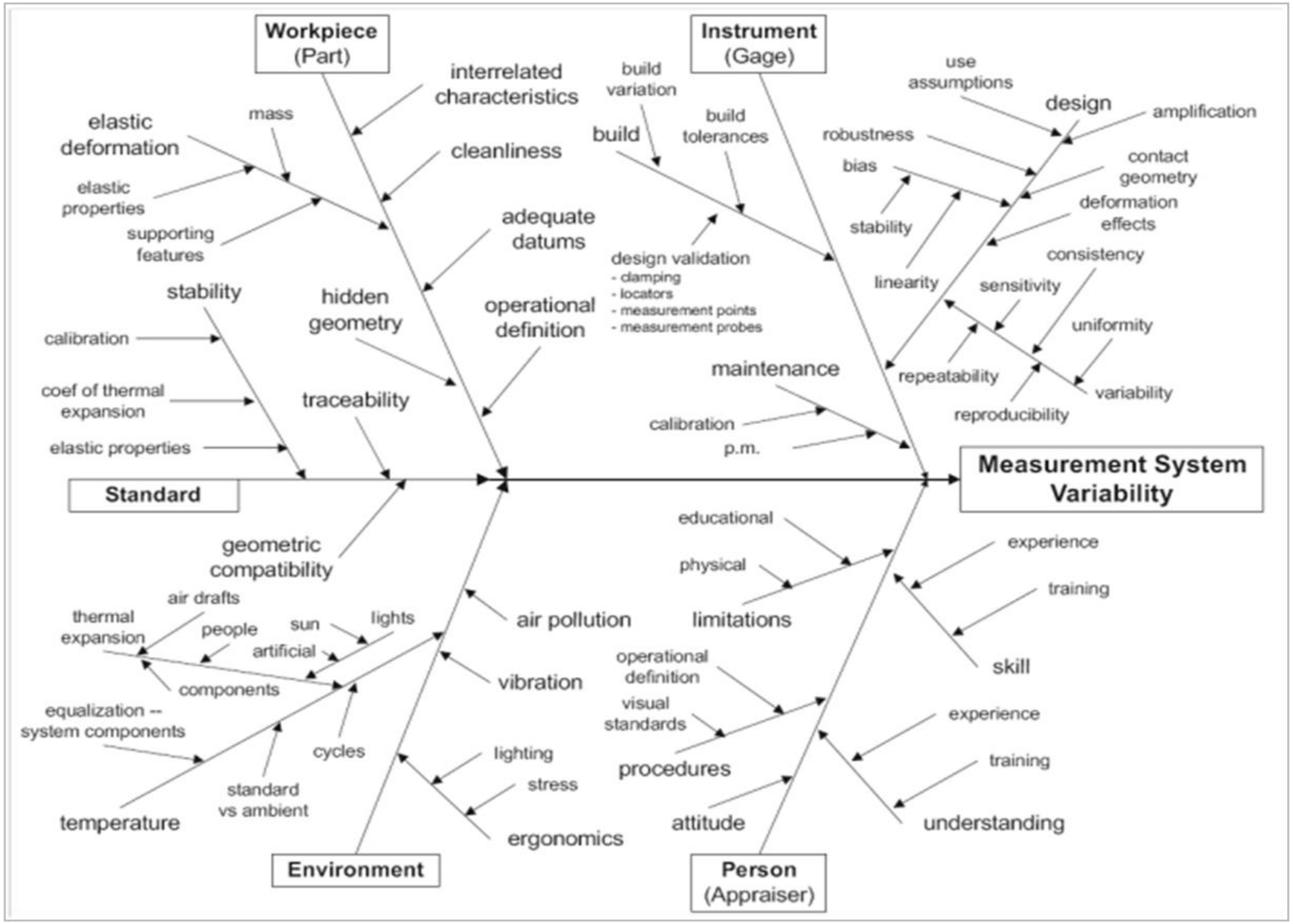

Figure 4-7 Measurement Systems Variability in Fishbone Diagram (AIAG, 2010)

Chapter Five: Materials Evaluation of Helander Alloys – experimental study

5.1 Introduction

Material uniformity both at the physical and chemical levels is of high importance in all manufacturing industries. There are also variations in machine time operations and process methods that influence machinability which are constantly under review by industry to improve product quality. Groover (2002) states that there are two types of variations in manufacturing: random variations that are caused by factors such as raw material, machine cycle and machine vibration together with assignable variations that are caused by something in the process. Examples are defective material and operator mistakes. The focus here is to minimise random variations by examining the microstructure of raw materials.

Different metal alloys (high-carbon/low-carbon steel, aluminium and superalloys) require different cutting speeds and are worked at different rates due to their hardness and chemical compositions. A review of the literature failed to reveal an acceptable material properties standard to minimise variations in machining Inconel 718 in terms of feed rate, tool life and the surface finish quality. The term feed and speed is widely used by machinist as a measure to adjust their machine to. Figure 5-1 shows the basic concept of feed and speed in lathe machine. Spindle speed (red arrow) is the speed of the work-piece (rev/min). The yellow arrow shows the speed (m/min) and refers to “cutting speed" or "surface speed”. The green arrow is the feed rate along the X-axis (mm/rev) and the blue arrow is the feed rate along the Y-axis (mm/rev). The red arrow represents the spindle speed (rev/min – RPM) (Southbaymachine, 2009).

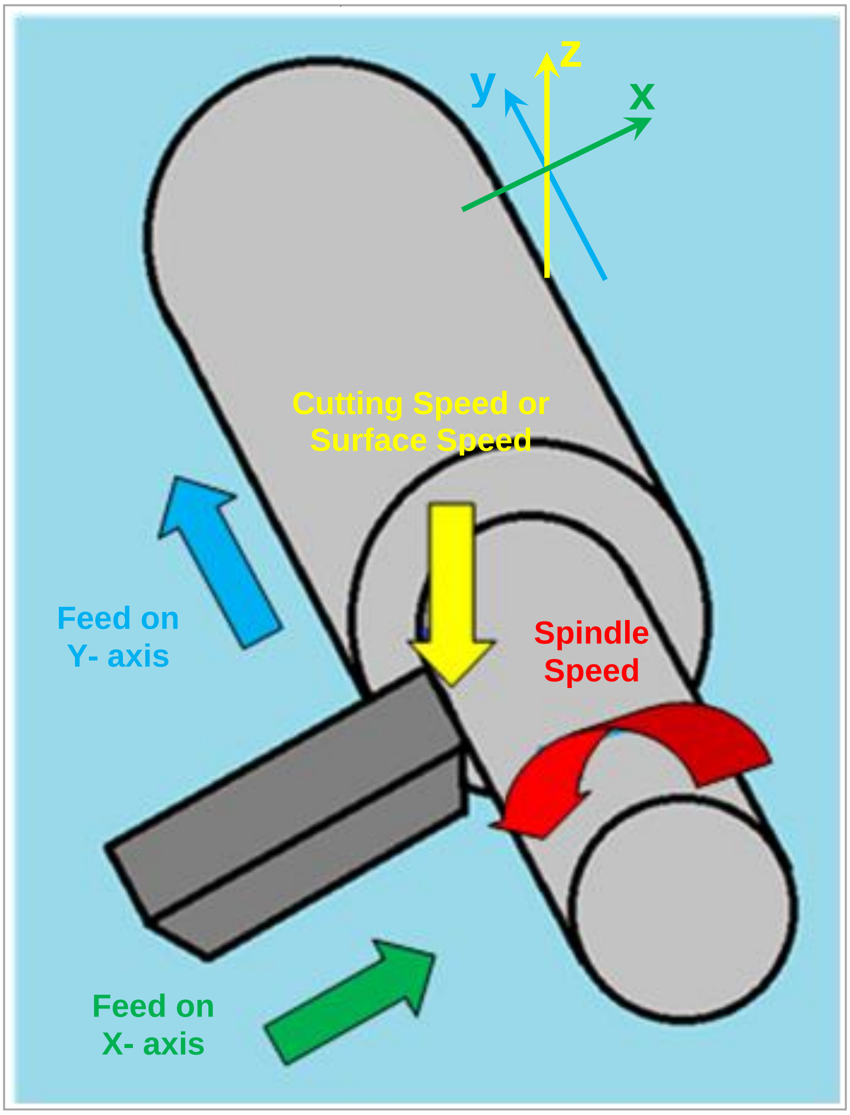

Figure 5-1 Speeds and Feeds (courtesy from Wikipedia/speeds and feeds)

Hence this research has investigated hard metal alloys in more depth by evaluating the chemical compositions and physical properties of different batches from different suppliers. The composition of elements in hard alloys is expressed as a percentage with lower and upper limits and variations in composition within these limits determines the ease or difficulty of machining. The vibrations, noise and uncertainties in dimensions on components while machining are caused by:

- Chemical properties
- Mechanical properties
- Inappropriate machining parameters (e.g. feed and speed)

It has been reported by machine operators at Helander that variations in materials in some cases cause vibrations in turning machines as well as unusual noises from the machining operation. This can be due to lack of uniformity in mechanical and/or chemical composition of the metal alloys. In order to take corrective actions, an experimental study of superalloys has been conducted by assessing the effect of chemical compositions on hardness (before and after heat treatment) and by imaging microstructure.

The thermal expansion coefficients of superalloys are low relative to other metal alloys. However small changes in density, due to variation in machining conditions mainly due to density in the component, have an impact on the dimensions of manufactured parts and assemblies of parts machined from Inconel 718. Inconel 718 and other nickel-base superalloys have densities between 7,800 and 8,900 kg/m^3 (CES EduPack, 2013). Density variations have a crucial impact on high value manufacturing with tight tolerances as it can cause mismatches between mating components (Donachie and Donachie, 2002).

5.2 Material Evaluation of Inconel 718

The variations between batches of materials (Inconel 718 alloy) have become apparent from machining operations at Helander. Helander machine operators claim that some batches of Inconel 718 are softer and easier to machine compared with others, resulting in less tool wear. Variability in machinability relates to variations in composition, heat treatment specifications and grain size/structure. As part of this study, a sample of Inconel 718 metal was taken to a materials preparation lab for microstructural analysis (Figure 5-2).

The specimens were cut at different orientations (shown by red lines in Figure 5-2) from wrought Inconel 718, mounted in resin and lapped and polished for microscopical analysis. The next stage was to etch the specimens in order to reveal the grain structure. The aim of this process was to compare batches of materials from different suppliers and discover the effects of material variations on machining. The process used for grinding and polishing Inconel 718 is shown in Table 5-1.

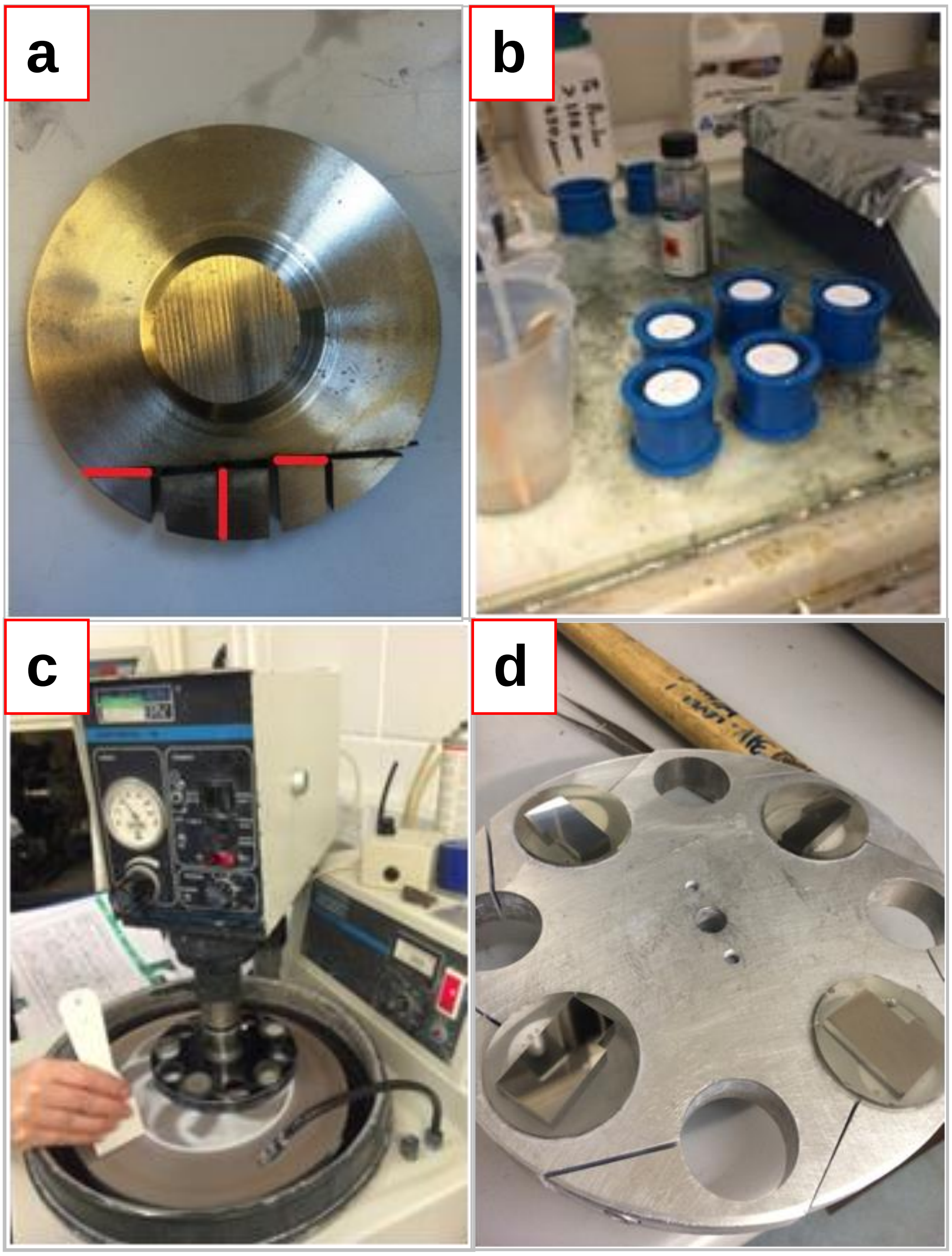

Figure 5-2 Preparation of polished sections for microscopical analysis (a) cutting specimens from an Inconel 718 bar, (b) mounting specimens in resin, (c) lapping mounted specimens and (d) finely polished sections

Table 5-1 Grinding and polishing method used for Inconel 718

Stage	surface	Lubricant	Particle Size	Head Rotation	Speed, rpm	lbs/ Sample	Time in minutes
Planar	SiC	Water	P180	Clockwise	150	5	1, repeat until plane
Planar	SiC	Water	P500	Clockwise	150	5	1, repeat if necessary
Planar	SiC	Water	P1200	Clockwise	150	5	1
Final Polish	Chemo-Met	None, but wet with water, then remove water before use	MasterMet 0.05µm silica	Counter clockwise	120	6	4, repeat if necessary

Kalling's No. 2[8] etchant was used to etch the specimens, as shown in a polarised light optical micrograph (Figure 5-3).

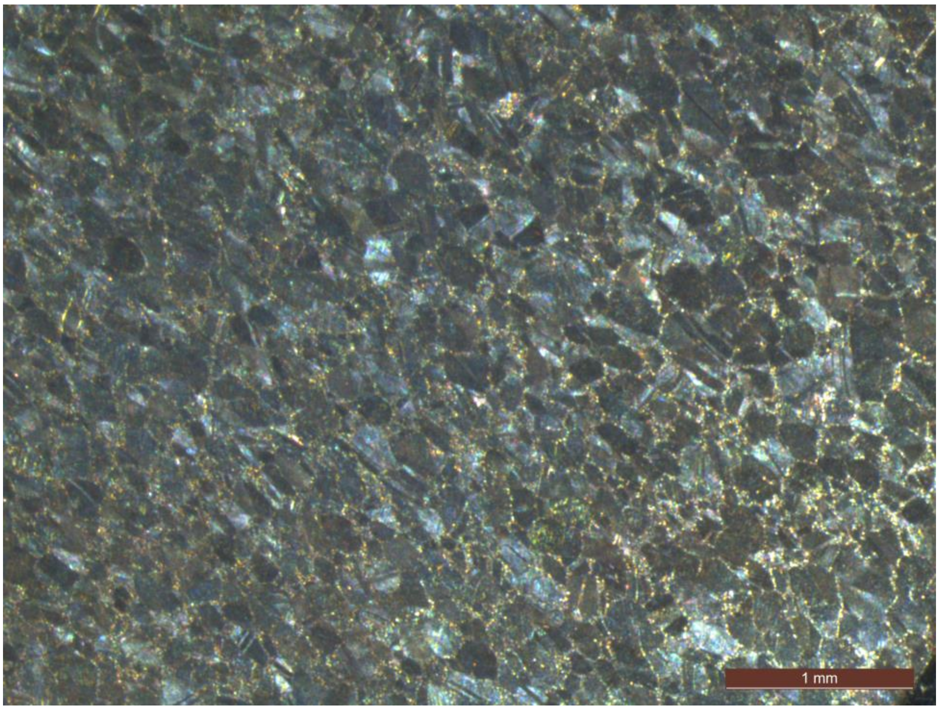

Figure 5-3 Microscopic image of the Inconel 718 after polishing and etching process

The microscopical images (Figure 5-4 to Figure 5-6) captured at different depths from the surface of Inconel 718 after machining (see Figure 5-2a) reveal fewer small grains near the surface (Figure 5-4) due to the heat generated during cutting/machining. This micro-structural change introduced by the machining process causes dimensional inaccuracies as a function of time (Dudzinski et al. 2004). These inaccuracies cause problems when it comes to assembly, which is why finished parts with tight tolerances were returned to Helander for rework by the customer. Large grain sizes help to prevent creep, while smaller grain sizes enhance strength and fatigue resistance (Campbell, 2006). The size of grains can be related to the 100µm scale bar. The depth of each section from surface of the alloy is shown in the image labels.

[8] Kalling No.2: 2.5g $CuCl_2$, 50ml Concentrated HCl & 50 ml Ethanol

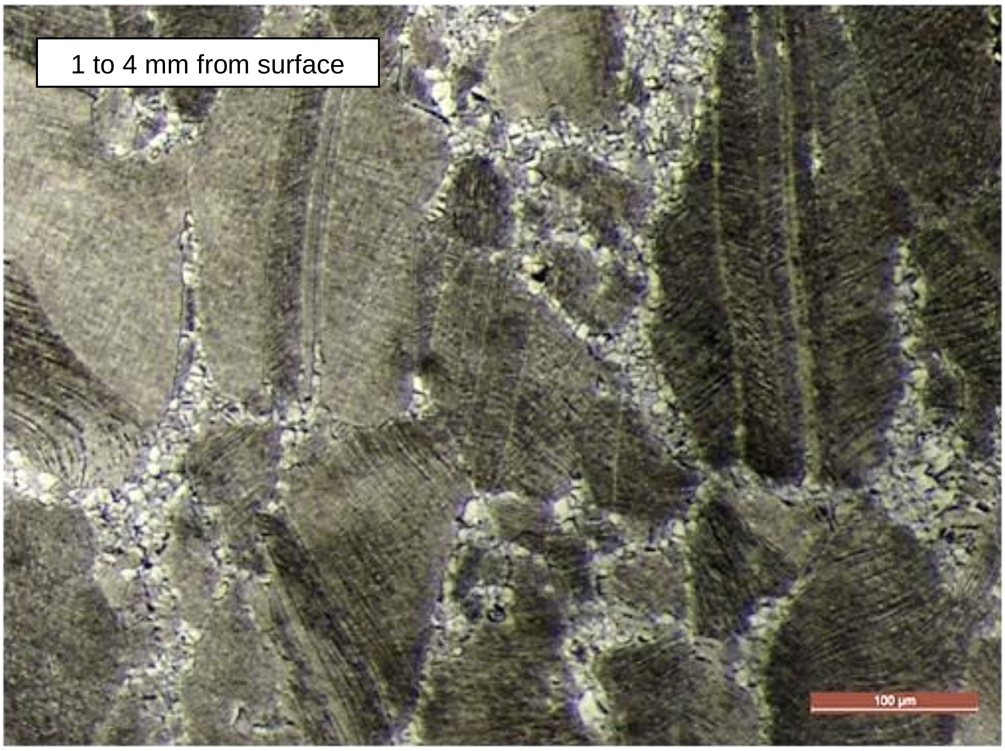

Figure 5-4 Inverted Reflected Light Microscope images of Inconel 718 - grain size ASTM 5 – Image is from near the surface of machined alloy

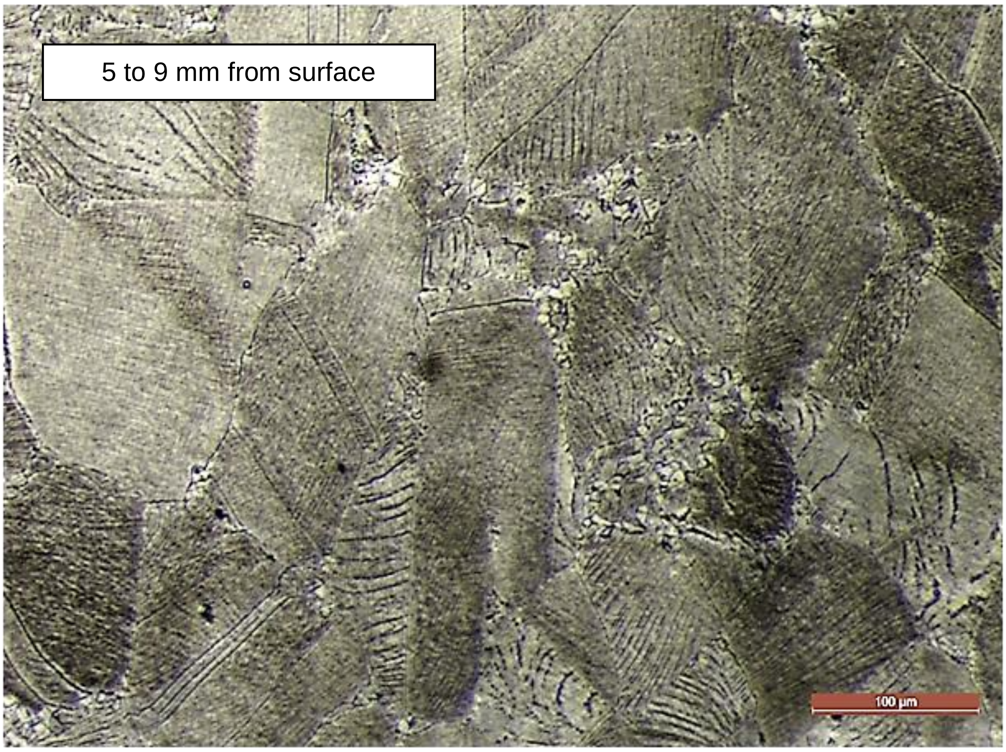

Figure 5-5 Inverted Reflected Light Microscope images of Inconel 718 - grain size ASTM 5 – Image is from a depth of 5 to 9 mm in the machined alloy

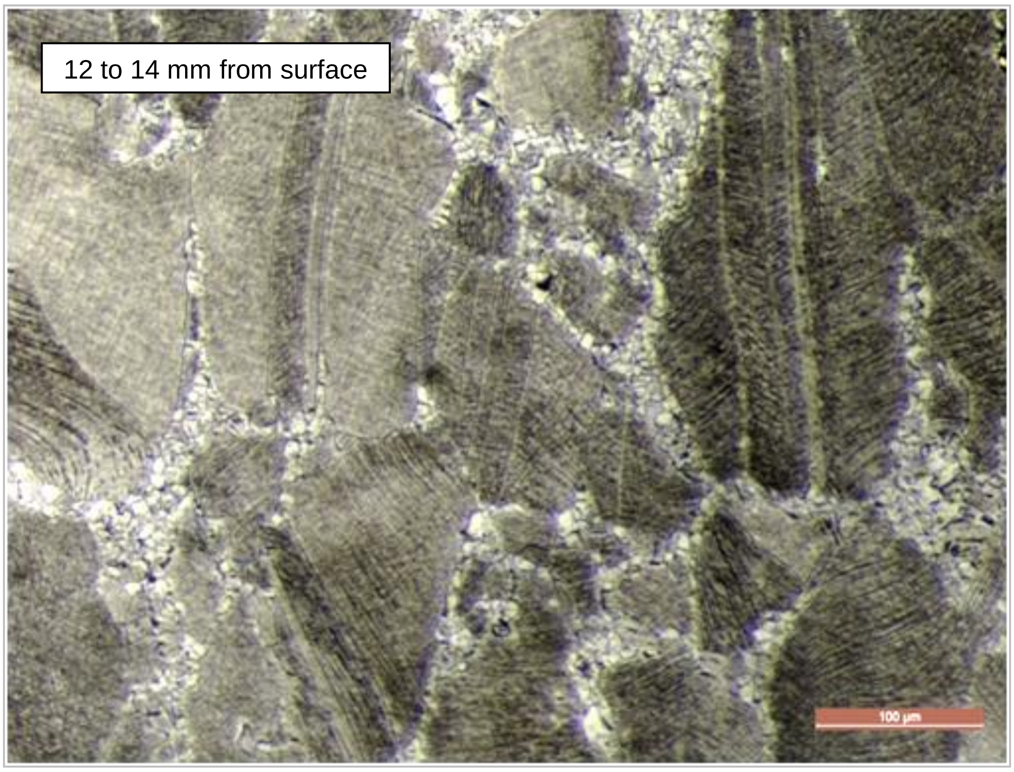

Figure 5-6 Inverted Reflected Light Microscope images of Inconel 718 - grain size ASTM 5 – Image is from the surface of the machined alloy

Images in Figure 5-4, Figure 5-5 and Figure 5-6 show that the orientation of individual grains varies. Twin boundaries are visible on the surface of grains. The results also show that the grain sizes and continuity of grains are not uniform across the same sample. These inconsistencies are due to the heat treatment procedures applied to the parts. The machining and cutting operations are performed on the outer surface of the sample piece. Heat is generated due to friction between the tool and the part surface in the machining process. This heat acts to harden the surface of Inconel 718 machined parts due to the fast cooling rate (air cooling) that promotes smaller grain size. Smaller grains possess higher strength and hardness. Furthermore, small grain sizes - especially on the surface – create stress at the grain boundaries (Groover, 2002). This stress creates non-uniformity at the surface, which could be large enough to change the desired dimensions during the machining process. Some of the vibrations and unusual noise in turning operations may be due to changes in the mechanical properties of Inconel 718 during different operations.

Hardness tests were performed with a Vickers hardness test machine equipped with a pyramid diamond probe and load of 20Kg. A typical diamond shaped indent is shown in Figure 5-7.

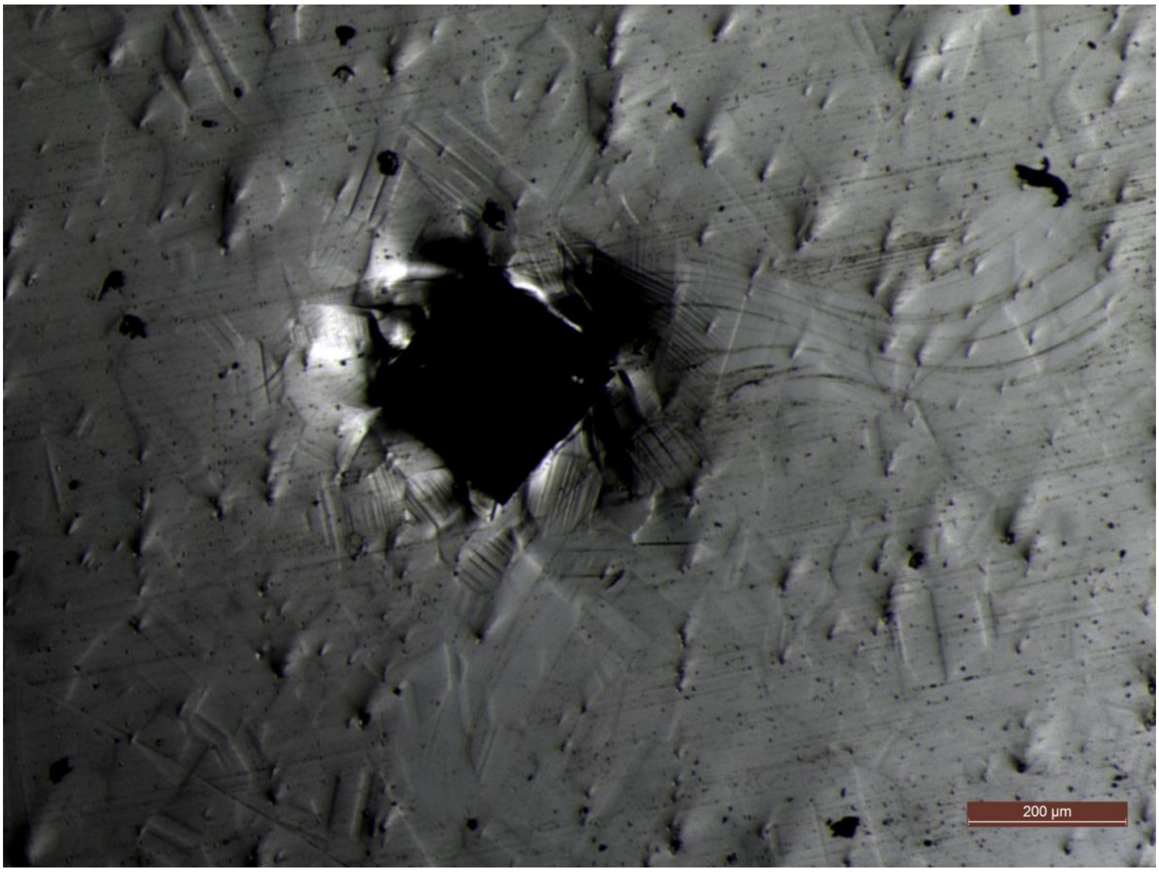

Figure 5-7 The indentation of hardness test on Inconel 718

Results of the hardness test are shown in Table 5-2. After machining the hardness of Inconel 718 at different depths from the surface shows the surface is considerably harder than sections inside the bar of the alloy. This is the result of age hardening on the surface of Inconel 718 due to the localised high temperature during machining as explained in the literature review chapter. The values in these tables might be different to values of as-received Inconel 718. These values can be different in other situations depending on the composition and condition of the specimen tested.

The results of the hardness test are shown in graphical format in Figure 5-8. As shown the hardness of the bar at the surface is significantly different to the hardness level in the sections in the deeper part of the alloy. This is due to age-hardening effect of the alloy as a result of the high temperature of the machining operation. The main reason for age hardening is the relatively poor thermal conductivity of Inconel 718.

Table 5-2 Results of Hardness Test at different depth of machined Inconel 718

	Specimen number	1 to 4 mm from surface (HV)	5 to 9 mm from surface (HV)	12 to 14 mm from surface (HV)
Surface	S1	429	NA	NA
	S2	426		
	S3	432		
	S4	420		
	S5	429		
	S6	435		
	S7	429		
Hardness	Average	429 HV	NA	NA
	Standard Deviation	4.72	NA	NA
Middle	M1	NA	407	NA
	M2		404	
	M3		401	
	M4		404	
	M5		399	
	M6		409	
	M7		404	
Hardness	Average	NA	404 HV	NA
	Standard Deviation	NA	3.36	NA
Centre	C1	NA	NA	407
	C2			394
	C3			399
	C4			396
	C5			401
	C6			404
	C7			401
Hardness	Average	NA	NA	401 HV
	Standard Deviation	NA	NA	4.46

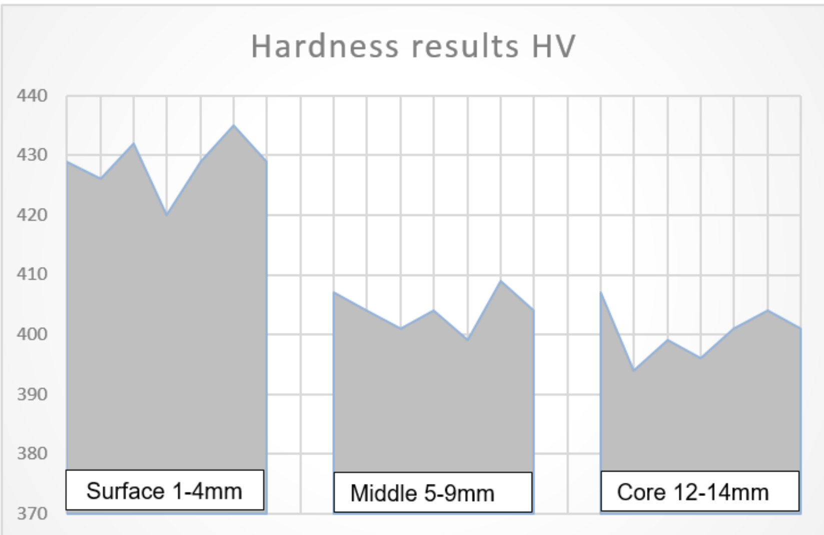

Figure 5-8 Results of hardness test on three areas of Inconel 718 bar after machining

ASTM method E112 includes a chart method for determining average grain size (Figure 5-9). Ni-based superalloys are mostly used in cast and wrought forms.

Moreover, a grain aspect ratio is determined in accordance with the ASTM E112-13[9] standard as a means of controlling properties.

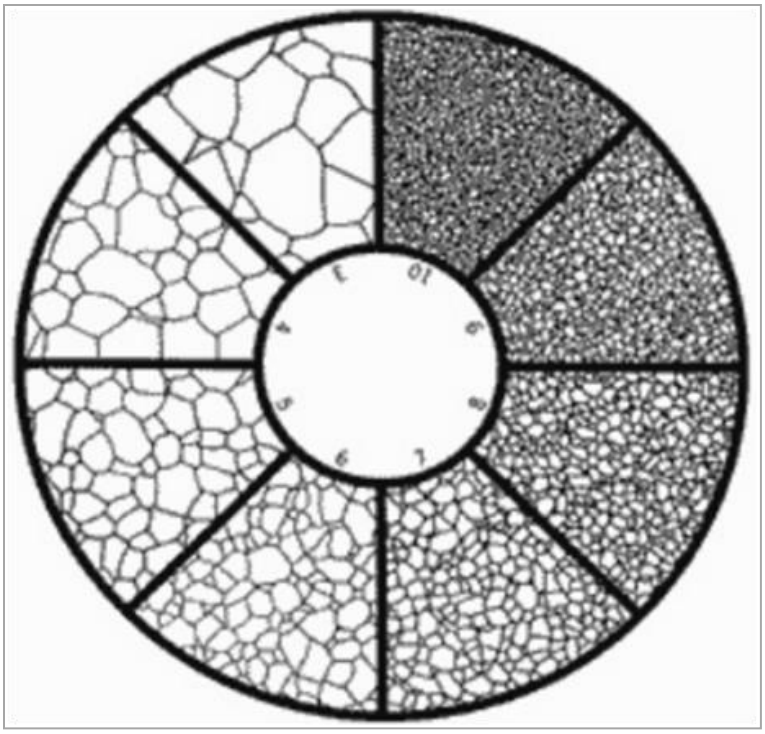

Figure 5-9 Chart method to determine the average grain size (ASTM method E112) for 100X magnification (Amrutiya, 2015), ASTM numbers are shown in the centre of the chart

The sample used for analysis in this research has a total average sample direction (longitudinal) ASTM No 5. Based on ASTM E112 standard the grain size number G is defined by the equation in below:

$$N_{AE} = 2^{G-1}$$

where N_{AE} is the number of grains per square inch at 100X magnification (Amrutiya, 2015).

As shown in Figure 5-10 grain structure differs across the section of the bar due to temperature profile across the bar during the machining operation.

[9] http://www.metallography.com/grain.htm

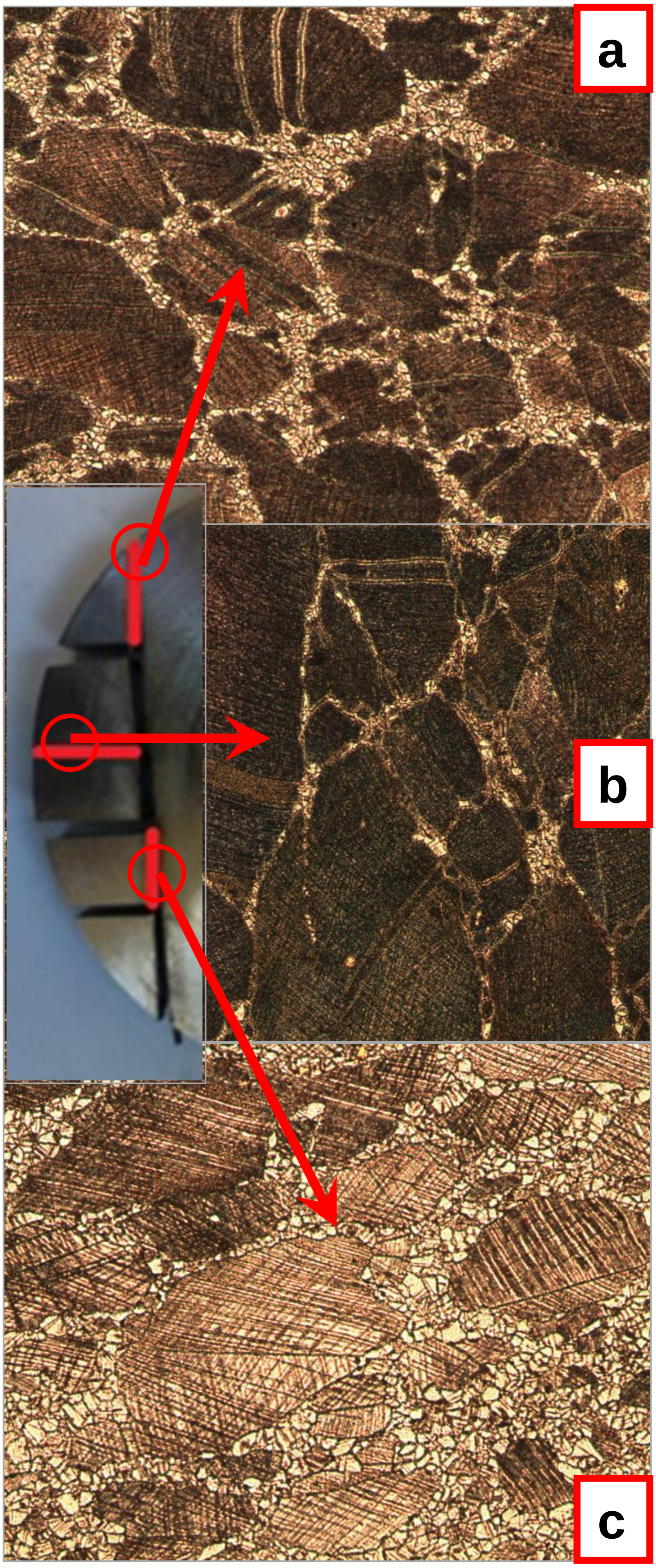

Figure 5-10 Inconel 718 sample from different orientations at the same magnification indicated by arrows: (a) image at 2mm from the surface, (b) image at 5mm from the surface (c) image from core section of the bar 10mm from the surface

In the image labelled as ‘a’ close to the outer surface of the bar the grains are harder in comparison to grains imaged in image ‘b’. The smaller grains at the grain boundaries are a precipitated second phase. There are fewer smaller secondary precipitated grains in image ‘b’. Conversely, the microstructure in image ‘c’ seems to be more unaffected by heat and machining effect and consists of more small secondary phase grains and larger primary grains suggesting that the thermal profile from the surface to the interior of the machined part has a critical effect on microstructure. All images are from the same bar with grain size ASTM No.5.

5.3 Hardness measurement of commercial Inconel 718 alloys

Due to witnessing the material variations on the same metals it is decided to choose an alloy as the case study and order the metal from different suppliers and different melts. In this practice three suppliers of raw material was chosen and three samples of Inconel 718 with the same dimensions ordered. The chemical composition for each alloy is shown in Table 5-3.

Table 5-3 Chemical analysis of sample alloys based on their certification test

Material	C	S	Cr	Ni	Mn	Si	Mo	Ti	Nb	Cu	Fe
Sample 1	0.025	<0.001	18.5	53.6	0.05	0.07	3.05	1.01	5.16	0.04	17.88
Sample 2	0.019	<0.001	18.6	52.8	0.04	0.05	3.06	1.01	5.09	0.03	18.64
Sample 3	0.019	<0.0003	17.6	53.7	0.06	0.06	3.01	0.94	4.99	0.03	BAL

Parts were heat treated under the solution annealed (age hardened) condition with specifications in below:

Sample 1 1026°C/2hours/water cool + 774°C/7:28hours/air cool

Sample 2 1026°C/2hours/water cool + 774°C/7:28hours/air cool

Sample 3 1023°C/2hours/Air cool + 779°C/7hours/air cool

So far the variations in chemical composition and the variations in heat treatment are in the process that can have an effect on mechanical properties. As explained in section 3.4 of the literature review, the localised heat treatment effect is the reason of the harder material in Inconel 718 (Ezugwu and Tang, 1995). The results of Rockwell hardness (HRC) tests performed by a third party before machining are listed in below:

Sample 1 38.8 HRC

Sample 2 39.7 HRC

Sample 3 36.2 HRC

Parts are machined to similar diameters. The same feed 0.3 per revolution and speed 50m/min and inserts are used to machine the parts and verify the machine load on each component. For this practise the heat resistant square carbide insert SNMG 120408 S05F designed for rough machining on <35 HRC Titanium and Iron based alloys (Sandvik, 2010). There were three runs of machining on each sample performed and results shown in Table 5-4.

Table 5-4 Results of the machine run on 3 samples (average of a minimum of five hardness tests in each case)

	Sample 1	Sample 2	Sample 3
Load percentage 1st pass	28	28.5	29
Load percentage 2nd pass	26	26	26
Load percentage 3rd pass	26	26	26
Hardness HRC after 3rd pass	39.4	40	38.8

The machine load on each sample shows that after the first run the machine load comes to a constant figure of 26%. This represents the variations that exist on the first run due to the fact that both material and insert are cold. Also the hardness test after material preparation shows the three samples are marginally harder due to the machining surface hardening process on Inconel 718 (explained in section 3.4 of the literature review).

In this chapter the author researched in the material characteristics of Inconel 718, one of the main materials used by Helander. Inconel 718 has certain reaction to heat while machining that brings variations to machine parameters. These variations can be to change the speed and feed for material removal. Some of these variations can be the product of variations in chemical compositions that can be different from different batches that can have a contribution in measurement instability of the component.

Chapter Six: Process Control and Process Verification

6.1 Introduction

At the SME level, different customers require different levels of verification and documentation. In recent times, Helander's main area of expertise was oil & gas. The documentation requirements for this industry are far less in comparison with other sectors that Helander has recently joined. In this chapter, the requirements for the main customers in oil & gas are reviewed and examples are chosen from the same industry sector.

The Supplier Requirement Procedure (SRP) or customer flow-down requirement, as a more general term, is a contractual document that customers want their suppliers to work towards. This document is attached (or referenced) to every single order from the customer indicating main and generic requirements and, where needed, subordinate documents accompany the order. The objective of the SRP is to define and communicate the minimum quality deliverables required by the customer from Helander outside of any specific product file requirements.

For example, one of Helander's suppliers provides a "Material Requirement Document" as a secondary requirement for each alloy. At Helander, metal alloys are received with a "Delivery Ticket" and a "Test Certificate" provided by the original supplier. Each batch should be verified by a third party specialised in testing materials prior to issuing the "Test Certificate". There is also a "Goods Received" note that Helander's inspectors check against purchase orders to ensure parts are of the correct specification. In this case, there is a specification for grain size, hardness, and chemical composition that must be used as a guideline for verification in "Goods Inwards" before the raw material passes to the production department. This process should be robust enough to identify any errors from suppliers.

Product control deals with mechanisms and algorithms for maintaining the output of a specific process within a specified range. It can be categorised as discrete (manufacturing processes), batch and continuous (SPC). A process validation is the process of checking a product and verifying whether the product meets the requirements of the design and intended purpose. The following section outlines a study on gauge R&R (technique that uses an analysis of variance to assess a measurement system) performed at Helander, showing how the process was conducted and explaining the verification methods. Additionally, two sample parts are analysed separately, highlighting the potential cost savings for each product subject to having all the documentation in place.

6.2 Methods of Process Control (PC) and Process Verification (PV)

There are various different standardised processes for Process Control & Process Verification in different industries, which include FAIR (First Article Inspection Report), PPAP (Production Part Approval Process), PFMEA (Process Failure Mode Effects Analysis), and APQP (Advanced Product Quality Planning) that are all required for NPI (New Product Introduction) process. One of the main requirements for almost all of these processes is gauge R&R study. Gauge R&R is used to understand the amount of variation in the measurement system via a statistical tool. It will highlight the main cause of the variation which can result from the measurement method, the person taking the measurement or the measurement device itself.

It is worth mentioning that not all nonconformities are a result of the machining process. As explained earlier, the machines and measurement systems have contribution on producing non-conformance parts. Preventive and predictive actions, such as the one developed by Renishaw (2014) Figure 6-1, need to be accurately developed in order to obtain the right results from methods like SPC or from investigations such as the troubleshooting approach. As shown, the process foundation and process setting are in the early stages of process variations. For instance, machine maintenance and process design come at the very first stage of variations. It is essential to have machine verification to check issues related to linear, positioning, yaw, straightness, roll and squareness of axis on CNC machines. Any of these errors can potentially cause the machine to deviate from the programmed circle path (Renishaw Training Manual, 2010). There is a need to have a standard machine set up sheet for each job on each machine. This machine setup sheets should clearly explain the tools and their offset from the job. The other details should be in the machine set up sheets includes, data such as which tool should be used for each operation as well as tool holder, insert, tool projections and tool offsets. Other documents required are stage drawing and measurement instructions for in-process control and also tool monitoring and on-machine verifications that can be identified via SPC method. Finally, data logging should take place to establish historical records and in some cases to compose first article inspection reports (FAIR).

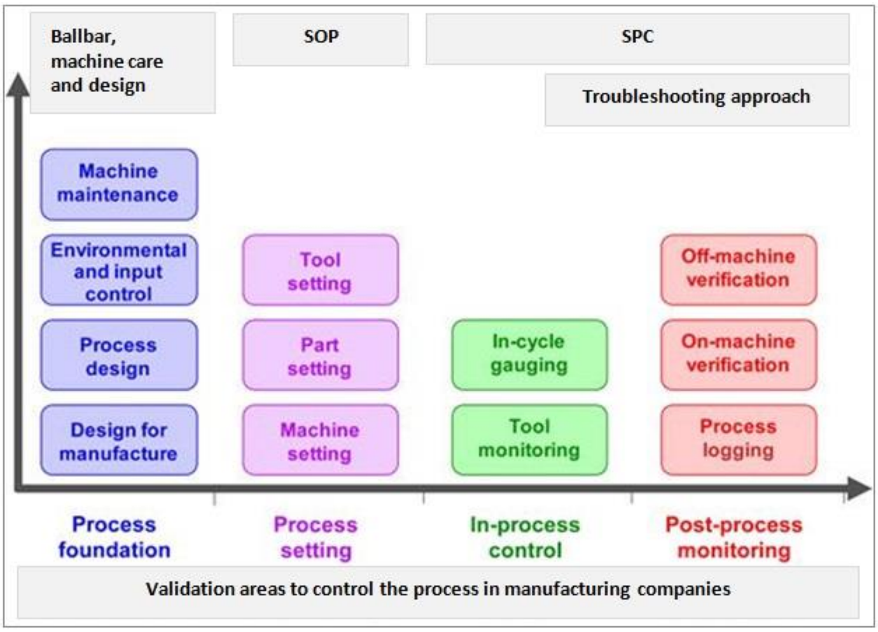

Figure 6-1 Process control framework (adapted from Renishaw Training Manual, 2010)

On-machine measurement probes for SPC can be verified with gauge R&R studies to make sure that the measurement system can adequately distinguish accepted and rejected parts. Gauge R&R also verifies the stability and accuracy of the measurement process within a range of parts. Helander company were originally not verifying their measurement system at the start of the research, based on the Gauge R&R method. The method was introduced and implemented at Helander to show the use of measurement tool for the correct dimensions required. Currently, this practice is performed at Helander for a range of part dimensions with different tolerances in order to establish a systematic approach for improving Helander's measurement capability and process confidence levels.

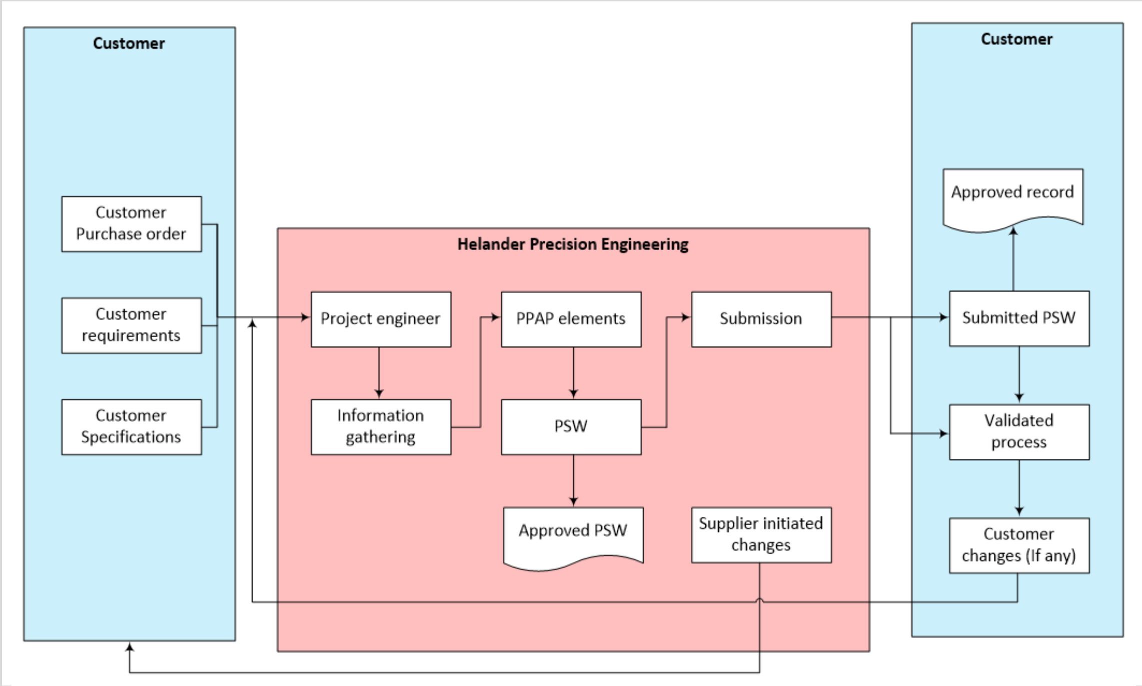

Figure 6-2 The process of PPAP at Helander

International quality standards for manufacturing continue to increase and many companies are requesting their suppliers to use PPAP. Created by the automotive industry, PPAP is a risk identification and mitigation process used as proof to the customer that the process is reliable and repeatable. As this process is costly and time consuming, other industries have their own format of PPAP[10] to match to their own needs. The purpose of using PPAP is to ensure better communication and collaboration between customer and supplier, which results in less uncertainty for each side during production (Shrotri et al. 2014). When a change occurs to any elements of PPAP (Appendix 1), customer notification is required, and sometimes, the Production Submission Warrant (PSW) (Appendix 2) as the final element of PPAP has to be resubmitted (Kartha, 2004). The process of PPAP is to ensure that all manufacturing challenges are reconsidered by different engineers in manufacturing, production and quality teams engaged in the process of manufacturing the part. The procedure of PPAP is implemented at Helander with the use of bespoke IPI Solution (Integrated Process Improvement) software bought for this purpose. The following process is designed for Helander based on the chart shown in Figure 6-2.

The customer places the order with necessary specifications (i.e. drawings and material specifications) and their requirements (i.e. certificates and test results). The

[10] i.e. Aerospace version 18 elements and automotive version 21 elements

project realisation stage is carried out by the engineering team and after information is collected and analysed the PPAP co-ordinator will take charge of the project and hopefully submit the PSW to the customer. In the case of dispute, the PPAP coordinator will contact the customer for the required information. After submission the customer validates the PPAP process proposed at Helander. If there is an agreement on the method of manufacturing based on the customer needs then the PPAP will be approved by the customer and the production phase will be started at Helander. If not, the process feeds back to the initial customer specifications or requirements and the new order will be generated and sent to Helander.

6.3 Gauge R&R case study

One of the main elements of PPAP is measurement systems analysis (MSA). Gauge R&R study is one subdivision of MSA. In order to have a higher confidence level in the measurement of sensitive parts, more accurate measuring tools should be used. Measurements are made to different gauges, ranges, and tolerances. The tool gauge capability table for each measurement gauge reflects the level of confidence in the different tolerances that the tool can achieve. The results are reliable if the operator is trained to apply an appropriate standard measuring method. The capability of each measurement tool at inspection department is verified with gauge R&R and the results shown in appendix 3). In one of the first exercises in the KTP project, a gauge R&R study was conducted. Interpretation of the results demonstrated how unreliably the parts were being measured.

A gauge R&R evaluation was conducted at Helander using different measurement tools. The study was performed on a returned part from a customer due to non-conformity in measurement. The part was a drill shaft component with a required diameter of between 64.970 mm to 64.985 mm which gives 15μm tolerance for the outer diameter. The part was classified as oversized by the customer. This part was measured with a digital micrometer before delivery to the customer. When the part was returned by the customer, measurements showed that it was marginally oversized (Figure 6-3). The highlighted area shows the acceptable range of dimensions (64.970 mm to 64.985 mm). However, almost all of the measurement figures were oversized using the same measurement device. The study shows how parts being inspected several times are still outside the range of tolerance. Also the variations of readings demonstrate inaccuracy in the measurement system. The similarity of readings by operators A and B suggests that readings are precise, but the component is outside the acceptable range by up to almost 15 µm.

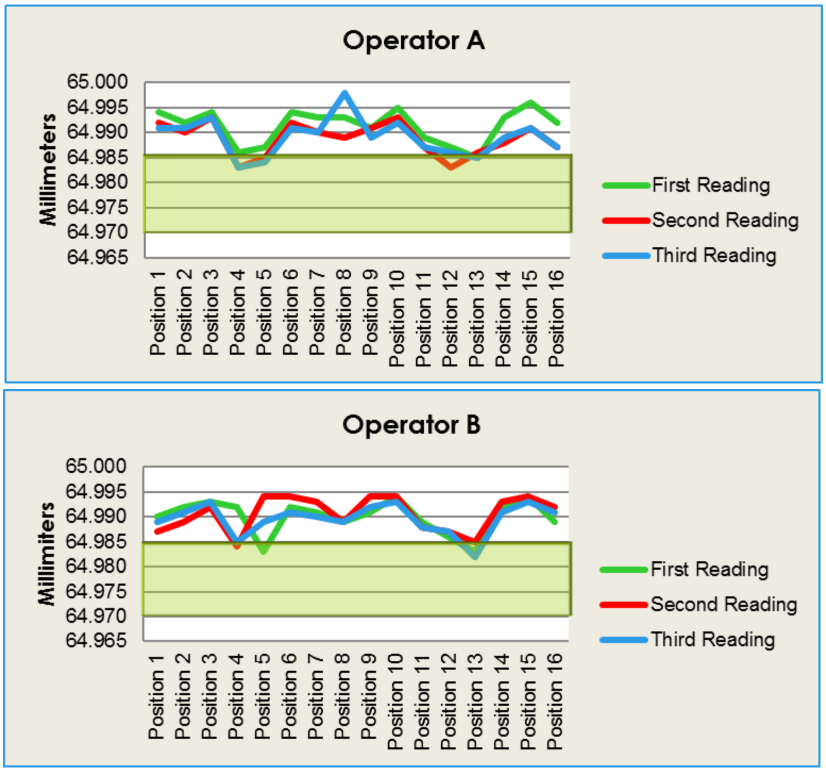

Figure 6-3 Measured figures against specified allowance tolerance (Highlighted green zone is indicating the acceptable range)

Table 6-1 Results of gauge R&R study with two different measurement tool (Results generated from study in Minitab) - 1) Comparator gauge 2) Manual micrometer

Results for Comparator

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	**0.0019027**	**0.011416**	**9.93**
Repeatability	0.0016931	0.010159	8.83
Reproducibility	0.0008682	0.005209	4.53
Operator	0.0000000	0.000000	0.00
Operator*Part	0.0008682	0.005209	4.53
Part-To-Part	0.0190694	0.114416	99.51
Total Variation	0.0191641	0.114985	100.00

Number of Distinct Categories = **14**

Results for Manual Micrometer

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	**0.0050404**	**0.030242**	**26.75**
Repeatability	0.0047539	0.028524	25.23
Reproducibility	0.0016750	0.010050	8.89
Operator	0.0000000	0.000000	0.00
Operator*Part	0.0016750	0.010050	8.89
Part-To-Part	0.0181594	0.108957	96.36
Total Variation	0.0188460	0.113076	100.00

Number of Distinct Categories = **5**

A gauge R&R study was performed on the outer diameter of a component. First the persons who are working with the organisation for that particular component are chosen. In this example 16 points on the same sample piece (shaft) are marked in a mixed order. Then three trials in a mixed order are taken from each operator and the results are recorded using Minitab software. The maximum and minimum values (standard deviations reflect accuracy) are used to calculate the range (Shrotri et al. 2014). The result shows how using a different combination of measurement tool and operator can have an effect on readings for the same components (Table 6-1).

As shown the total gauge R&R value decreased to less than 10% in the study with comparator gauge. This is due to selection of the appropriate gauge based on the gauge capability (see Appendix 3). The amount is the contributions of different elements into measurement system and the AIAG[11] guideline (Table 6-2) shows the descriptions for each range of variance.

Table 6-2 AIAG guidelines for the gage R&R table (Minitab, 2010)

%Tolerance, %StudyVar %Process	System is…
Under 10%	Acceptable
10% to 30%	Potentially acceptable (depends on the criticality of the measurement, costs, risks, etc.)
Over 30%	Not acceptable

Also the number of Distinct Categories value estimates how many separate groups of parts the system can distinguish. Minitab calculates the number of distinct categories by the equation in below (Minitab, 2010):

$$S_{part} / S_{measuringsystem} * \sqrt{2}$$

A comparator gauge that the customer uses at their inspection department was used as the measurement gauge for this study. The result of the gauge R&R study revealed that a micrometre used at Helander was not suitable for such a tight tolerance (15 μm). In addition to that, the operator may play a part in inaccuracy of a measurement method. The latter issue can be solved by a skills matrix review for

[11] The Automotive Industry Action Group (AIAG) recommends the use of 6s in gage R&R studies.

operators followed by trainings in GD&T (Geometric Dimensioning and Tolerancing) and uncertainty of measurement (measurement uncertainty budget)[12].

In order to verify the source of error for returned parts, the thermal expansion of the Inconel 718 alloy was examined. The thermal coefficient of expansion (thermodynamic property) of Inconel 718 is 12.8-13.4 microstrain/°C (CES EduPack, 2015).

This means that Inconel 718 will on average expand by 13.1 μm per metre per degree centigrade. Linear expansion of the part can be calculated via the equation in below:

$$L = \alpha * L (\Delta T)$$

Where

L is linear expansion (meter or inches)

α is Coefficient of Linear expansion of the alloy (constant) (m/m°C, in/in°F)

Δ T difference in temperature (°C , °F)

For this example:

$$13.1\ \mu m * (65\ mm/1000\ mm) * {}^\circ C = 0.8515\ \mu m$$

An approximate linear expansion of 0.8515 μm per degree centigrade will occur for this example which must be taken into account during measurement.

The Gauge R&R study proved to Helander that having the correct measurement system is a necessity to the business in order to comply with customer requirements. This issue was conventionally counted as less important as the company had the use to use their staff experience rather than systematic evidence on selection of measurement tools.

[12] http://www.muelaner.com/uncertainty-budget/

6.4 Control of the processes in manufacturing

Three common methods are introduced to control the processes in manufacturing organisations (Gillespie, 1988). These methods are part sampling, SPC and troubleshooting approaches. Depending on the sensitivity of the components, dimensional tolerances, volume and design of the components and/or value of the jobs, one or more methods should be considered for controlling the process. Part sampling is the method of part verification that works based on verifying a random sample of the quantity of batch that represents the uniformity of parts made by specific operation. It has never been easy for manufacturing companies to understand their confidence level in terms of how accurate and to what degree of flexibility parts can be made. This brings uncertainty in determining the most suitable manufacturing method as well as in controlling the product and process verification systems. Therefore it is necessary to develop a system for capturing the company's knowledge and expertise and reflect it into the MRP system. One of the key aspects of this system is measuring manufacturing and machining capabilities to a reasonable confidence level. An in-line control measurement system was introduced to address this concern.

At Helander inspection and verification of sample parts is done using a CMM machine or different gauges depending on the engineering specifications of the part and the capability of the measurement systems. This process dictates that if one item is rejected due to a specific defect, the whole batch should be inspected for that defect. Due to the nature of random selection in the batches, this process does not generate accurate and trustworthy verification, especially for high value and specification components. As mentioned in Portas' Law (Blunt and Knapp, 2013): "Random results are the consequence of random procedures", which is an issue of concern in this current research.

It has been proved that certain measurement devices are not capable of measuring tight tolerances (up to 15µ). This seems obvious in many cases; however when the tolerances are at the micron level it is challenging to decide what measurement tool should be used. The study on gauge R&R at Helander company along with the capability charts prepared by Rolls Royce SABRe (SABRe is the name of the project launched by Rolls Royce which stands for Supplier Advanced Business Relationship)

(Rolls Royce, 2013) and conducted at the Helander company are to be used as a guideline for using different measurement gauges.

At Helander company the use of parts sampling for batch manufacturing is very common in the case of high volume and less sensitive components. This involves the inspection of several randomly selected parts for each batch size. Table 6-3 shows the sampling plan in relation to the batch size.

Table 6-3 Sampling plan frequencies for high volume simple parts

Sampling Plan	
Batch Size	Sample Size
1 - 5	ALL
6 - 15	6
16 - 25	10
26 - 50	15
51 - 90	20
91 - 150	25
151 - 500	30
Over 500	35

The next stage is to keep control of the process by establishing a framework for sustaining the control criteria. The SPC system is a useful tool to manage the results and keep a record of the data. This way engineers have more control on the capabilities of the manufacturing. The next stage is to identify and eliminate waste to reduce lead time and cost. Research on data analysis shows both the SPC system and review of non-conformance parts were effective ways to discover the root cause of the failure in machining process. For instance, reducing lead time can be done by changing the cutting tool on machines at defined intervals. This can increase the quality of manufactured parts and ultimately reduce the cost due to rework. Finally, as shown in Figure 6-4 after the waste has been removed and variation has decreased, performance will have improved and the project will be at a high level of maturity and processes can be executed to keep the manufacturing system at zero defect level (Wilson, 2007).

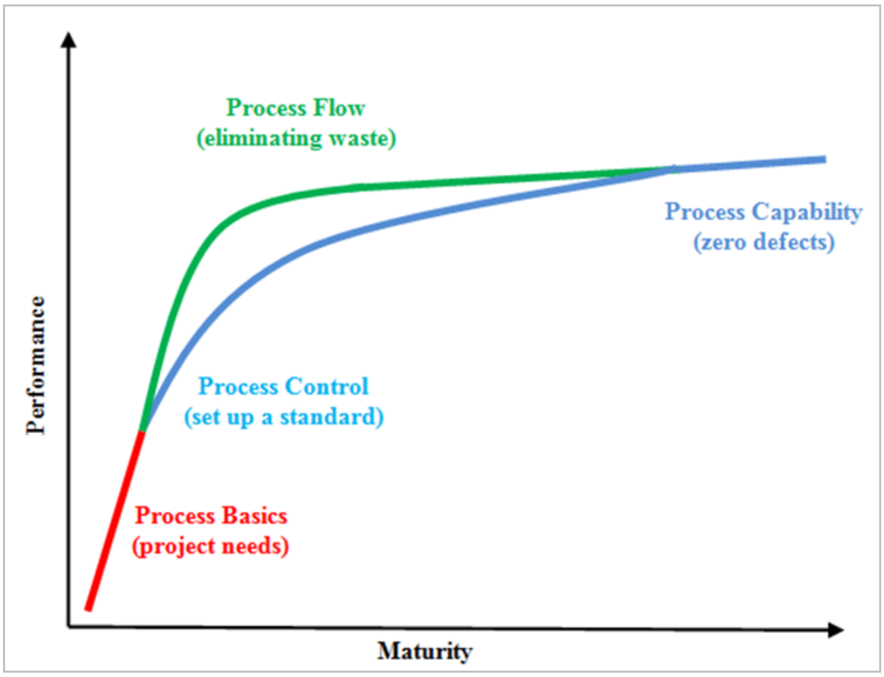

Figure 6-4 Performance vs. maturity (Wilson, 2007)

Manufacturing process control along with quality concerns are the two fundamental issues of any quality standard system. It is the focal task of the quality department to ensure the policies, operational procedures and processes are explained in a way that not only meets customer demand in a sustainable manner, but also ensures that a lean approach is considered. There is no doubt that in order to have a loyal customer, it is vital to have high quality parts delivered. This enhances the organisation's reputation and helps the company's growth and profit margin. In order to make non-defective parts on production lines, it is necessary to have a detail and full control plan for every operation. Describing the operational procedures of different workstations and ensuring there is no ambiguity in work instruction is one way to minimise the defects in manufactured products. As mentioned earlier, it is the manufacturing engineer's task to design the best method of manufacturing and take control of different documents for each operation. At Helander the manufacturing function is always tied up with many tasks to perform and the lack of resources in experienced manufacturing engineer is quite evident.

A set of documents such as tool schedules, quality standards, work instructions, machine tool program numbers, SOPs (standard operation procedures) and specific documents that refer to each operation are introduced. These documents are necessary for operators at the machine to perform the task correctly each and every time. It is difficult to change the mind-set of different operators to follow these instructions, but if the benefits of such systems are explained to the operators at different levels of expertise, changes can be implemented more easily and effectively (Coward, 1998).

At Helander, in line with KTP objectives mentioned in Chapter One, it was decided to work in the area of quality management and establish customer requirement and manufacturing process capability. For this purpose, the relationship between Helander and one of their major customers in the oil and gas industry was investigated. The main challenge in this research was to establish the requirements of the internal and external stakeholders, such as the shop-floor operators, team leaders, quality managers, and the customer's organisations. Two production parts were selected as a pilot study for a review of the quotation process at the company throughout the stages of contract review, acceptance of the order, engineering, purchasing, planning, manufacture, sub-contract process, inspection and wash and pack. These two parts were selected based on their complexity and continuity in production. One part is a simple product (Section 6.5) and the second part is a complex product (Section 6.6).

6.5 Case Study of Simple Product

This section examines the simplest product that routinely exists in a manufacturing. The part is very simple, low value, and produced in high volume within Helander. The schematic view of the part is shown in Figure 6-5.

As mentioned, this part is in production and therefore it is not going through the NPI procedure. In this case, the customer order references the following documents:

- Drawing No and issue
- General SRP document (SRP is a 30 pages document that is part of the contractual contract with the customer)
- Cleaning document (secondary document)
- Packing document (secondary document)

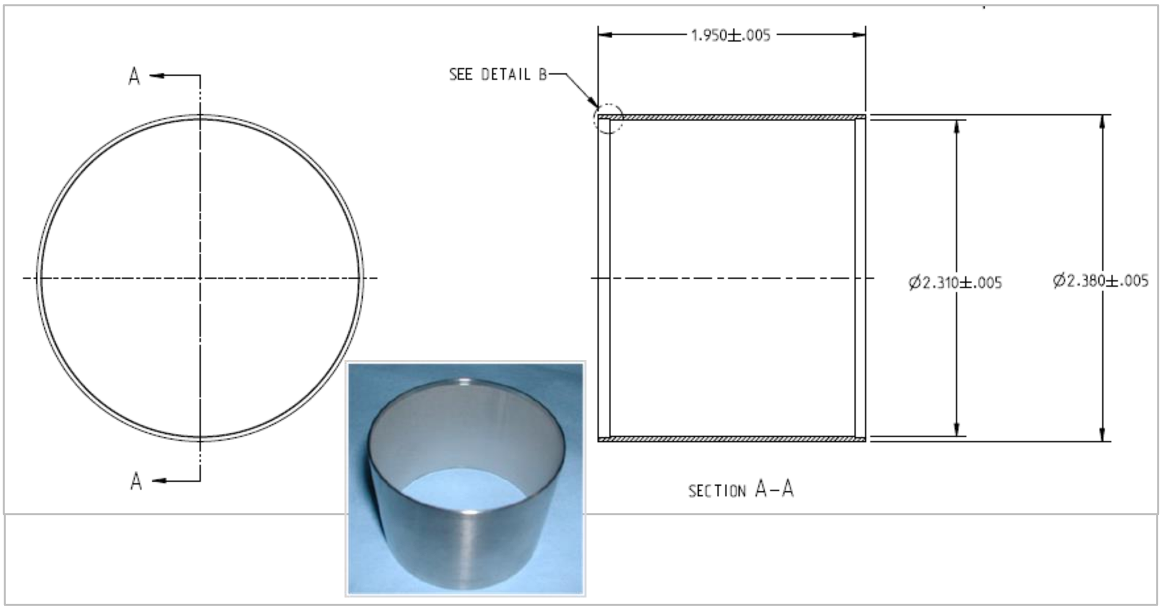

Figure 6-5 Sample Part

After reviewing the SRP issued by the customer and comparing the processes to Helander procedures, it became obvious that some processes were missing and/or not being followed by Helander. The best way to identify the deficiencies from Helander in response to customer needs is the compliance and deviation matrix), highlighting the supplier requirement document for Product A, showing the titles of the general SRP in the subject column and compliance/deviation/action (if required) for the other columns. The evidence for compliance items are listed in the Table 6-4 with references to the relevant document in the quality system and/or procedures in the quality workflow.

COMPLIANCE & DEVIATION MATRIX

Reference: Customer Supplier Requirements Procedure						Part No: Product A
Customer: OIL & GAS sector						
Para Ref	**Sub Para**	**Subject**	**Compliance**	**Deviation**	**Action**	**Evidence**
			Yes / No	Yes / No		
P.1						
P.2						
P.3		Implementation and Monitoring	Yes	No	None	Production and management review procedures
P.4		Health, Safety and Environment (HSE)	Yes	No	None	Helander HSE Manual
P.5		Quality Management System (QMS)	Yes	No	None	ISO 9001 standard
	5.1	Key Performance Indicators (KPIs)	Yes	No	None	NA
	5.2	Electrical Contract Manufacturer (CM) KPIs	NA	NA	NA	NA
P.6		Quality Control Plan (QCP) and Part/Process Control Plan (PCP)	No	Yes	Action	Part/Process Control Plan (PCP) HP 6 Iss 5 QUALITY PLANS
P.7		Change Notification Requirements	Yes	No	None	Contract Review (HP 32 Iss 1) and production procedure
P.8		Request for a one time/temporary deviation or change	Yes	No	None	NA
P.9		Control of Sub-tier suppliers	Yes	No	None	Technical date sheet/Standard Cleaning Procedure
P.10		Purchase Order (PO) Acknowledgement	Yes	No	None	Supply Chain Portal
P.11		Quality Records Retention and Maintenance	Yes	No	None	Quality records procedure
	11.1	Traceability	Yes	No	None	HP 7 Iss 4 TRACEABILITY
P.12		Cleaning	Yes	No	None	Wash and Pack W/O
P.13		Marking	Yes	No	None	NA
	13.1	Raw Materials	Yes	No	None	Goods inwards procedure
	13.2	Manufactured Products and Assemblies	Yes	No	None	W/O procedure
	13.3	Drill Collars and Subs	NA	NA	NA	NA
	13.4	Printed Wiring Assemblies (PWA)	NA	NA	NA	NA
	13.5	Critical Components of Dual Source Assemblies	NA	NA	NA	NA
	13.6	Single Chip Module (SCM) and Multichip Module (MCM) Assembly	NA	NA	NA	NA
	13.7	Requirements for ATEX and ATEX-Critical Parts	NA	NA	NA	NA
	13.8	Small parts	NA	NA	NA	NA
P.14		Inspection	Yes	No	None	Goods inwards procedure / Production procedure
	14.1	Mechanical supplier Inspection	No	Yes	Action	W/O to define the measurement value
	14.2	Raw Material Receiving Inspection	Yes	No	None	Goods Inwards precedures
	14.3	Electrical Contract Manufacturer (ECM) Inspection	NA	NA	NA	NA

Table 6-4 Compliance and deviation matrix (study on simple part)

After reviewing the lack of compliance in item P.6 (Control Plan), it became clear that there was no document and procedures to support the control plan document based on customer definition:

“The Supplier shall develop and maintain “Quality Control Plan” (QCP) and “Part/Process Control Plan (PCP)” for those parts requested by customer, either through Part and Process Qualification for new parts or for failure investigations on legacy part numbers. The PCP can be routers or router summaries, provided sufficient detail is listed to indicate how the supplier will maintain quality control of the given part”.[13]

Evans and Lindsay, (1999) explained the quality control plan as the description of activities/processes and tools that are essential to produce a product that meets the customer specifications while minimising variations. There are variety of templates for the quality plan, quality control plan and part/process control plan which exist on the web. Each company generates their own PCP in their desired method and bespoke to their own procedures. It is important to the customer that there are gates in the production to ensure that the PCP is in the production process and that it goes along with progress in production. Having PCP in production process decreases the risk of producing and working on non-conformant parts. It is often happening that the production capacity is taken by products that are already failed in previous operations and in-process inspectors didn’t fully understand it until the final inspection procedure. This will cause delay and uncertainty in delivering the parts to customer. This request can be performed only if the control plan exists as part of the work pack with the production pack for each batch of product. Therefore, the process map of product vs. process represents the engagement of the quality team right from the start of the procedure. The quality engineer should raise concerns regarding the quality issues and requirements of checking with the right tool at the right time and with the right level of inspection QCP document. For instance, as shown in Figure 6-6, level 1 inspection could be the operator with the gauge at the machine and level 2 could be inspected by a member of the quality team in a temperature controlled environment. In addition, the manufacturing engineering team should raise concerns with logging the data into record tables within the work-pack rather than simply checking and accepting the part as correct. Regardless of the measured value, the

[13] Schlumberger, “HPS/HCS/HFE/SDRM/SDTS” (Horizontal Pumping Systems/Houston Corporate Soccer Houston Formation Evaluation), DMS # T1000037, Revision AL

measurements should be recorded and stored by the tablet screens provided for each CNC machine. It was found on various occasions that the manufacturing engineer picks up this requirement during the planning and PFMEA process but fails to highlight the issue.

The process engineer (Level 1 area) acts as the interpreter between the manufacturing engineer and the shop-floor personnel and is responsible for ensuring that all these issues are written in the routing and are being followed. Other tasks of the process engineer include version control, giving training to shop-floor personnel (Level 0) on how to log data and interpret the data as well as maintaining records.

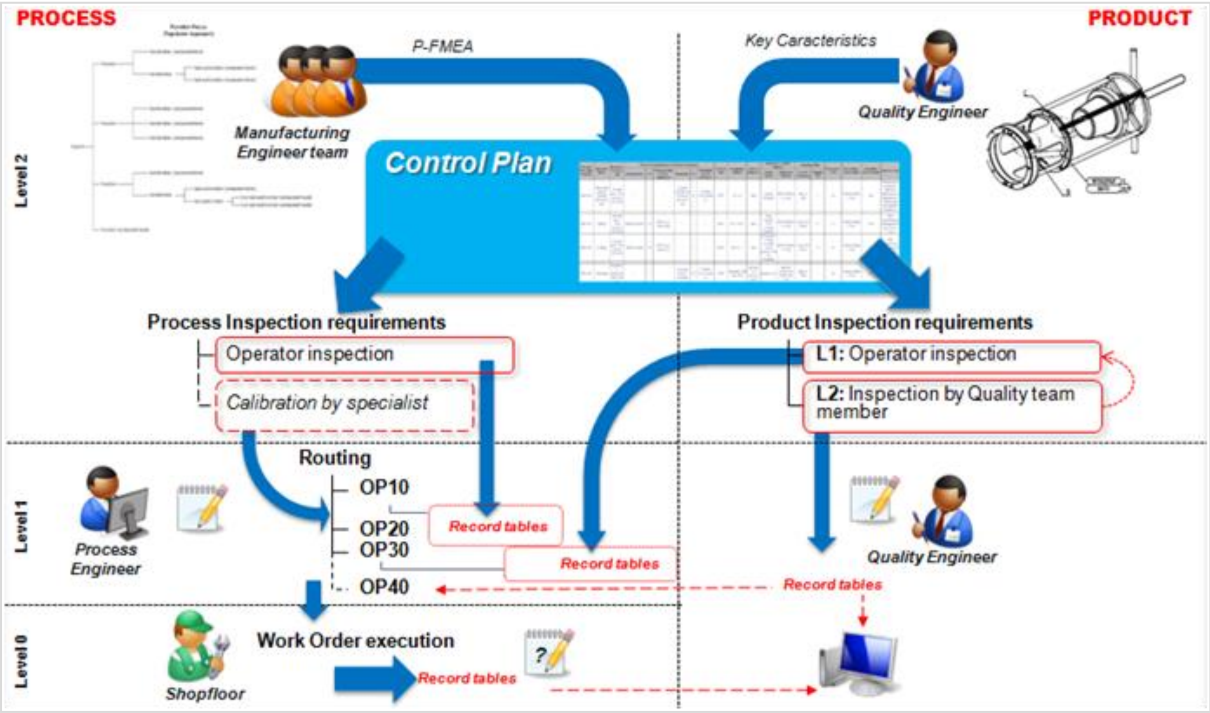

Figure 6-6 Product/Process Control Plan (Adapted from Airbus SAS, 2016)

The PCP document Table 6-5 is prepared to show how a in case of the simple product, part is produced, from receiving raw material to shipping the final product. In the designed form, information such as specific quality checkpoints, specific gauges to be used with serial number, the frequency of checks and control method can be found. Along with the control plan document for each batch, there is another set of documents attached with the parts as part of the work pack. These documents do not replace the route card. The purpose however is to support the route card. For example, there is no other method to explain the set up instructions unless it is documented and sent along with the route card.

Control Plan

Site/Supplier:		Helander Precision Engineering Ltd				Supplier No:			***	Control Plan Name/No:				Issue No:	01
Part/ Process Family:		Part Description			Part Number:	XXXX	Issue:		XX			Dated:	27/04/2015	Prepared by:	A Jamshidi
Process				Controlled Characteristics					Control Methods						
							Process Spec / Tolerance (Inches)								
Op. No.	Part No	Operation Description	Dept Work Centre	Design Key charecteristic	Process Input (X's)	Process key carecterestic	LCL	UCL	Process Output	Measurement Technique / Equipment Plant or Calibration Identifier	Sample Size	Sample Freq.	Control Record / Method	Reaction Plan / Follow Up	
10	SLB-XXX	Turn complete and debur	Turning (Unit 2)	Drawing No XX Iss XX	Engineering drawing (B3, B4, C3, C4)	W/O	Section A-A Ø XX ±0.005 H 1.945 Detail B Ø 2.317 W 0.080	Section A-A Ø XX ±0.005 H 1.955 Detail B Ø 2.319 W 0.085	Turning complete	CMM (1st off) "Go, No Go" Gauge # XX Gauge # XX Gauge # XX	100%	Each Batch	Operator Inspection / 1st off Inspection on Works Order (OP 10)	Quarantine Part / NCR / CAPA	
20	SLB-XXX	Inspect	Inspection (Unit 2)	N/A	Engineering drawing	NA	Visual		Post deburring inspection	N/A	100%	Each Batch	Operator Inspection (OP 20)	Quarantine Part / NCR / CAPA	
50	SLB-XXX	Wash and pack	Packaging (Unit 2)	N/A	Engineering drawing	NA	PDM # 100695196 Rev AB		Washed, packed and labelled products	N/A	100%	Each Batch	Packaging Operator (OP 50)	Quarantine Part / NCR / CAPA	

Table 6-5 Control plan for simple product

Due to a lack of existing up-to-date procedures on the start of this research, the setup document with controlling versions did not exist in Helander. This issue by itself is considered the largest factor which results in variations in repeated work with the company.

In Section 6.5, other sets of documents have been introduced to Helander which now accompany each batch are as follows:

- Manufacturing drawing (customer drawing)
- Operations route card (written by process engineer)
- Material document (proof of material verification and acceptance)
- Process change records (changes – if required – to master route template)
- Non-conforming part record (5 why questionnaire)[14]
- Additional material requisitions (for return/scrap purposes)
- Final inspection records (to record the measurements on the final stage)

After reviewing the SRP and realising the need for other documents to support the procedure, it was decided to modify the current forms and add other documents such as:

- Machines tooling setup sheet (machine set up instruction)
- Work instructions (stages/orders of work for each operation)
- Work instruction drawing (showing what tool for which face plus offsets)
- Stage drawing (simplified drawing for each operation, live drawing)
- Quality Schedule (replacing item 7 final inspection records)

The process of change at Helander takes a while until the shop floor operators get used to the new procedures. Due to this unfamiliarity and due to not having a set up instruction for machines, there were losses in time, variations in set up procedure, variation in products, scrap and rework. Adding to elements mentioned every time, the team leader of the site was responsible for setting up the machine, running the first product, and verifying the part to ensure the machine was set correctly before leaving it to the machine operator. The procedure set up is highly dependent on certain individuals (team leaders) to adjust the machines. During the machine set up, the machine operator was idle regardless of the time for machine set up (sometimes

[14] 5 Why is a technique used to explore the cause-and-effect relationships that causing a particular problem

more than 2 hours!). This also resulted in waste in the planning department as the variation in the set up time was unpredictable. The time required to perform one-batch impacted on the company capacity since it could take time away from the next batch that was planned on the machine.

The tools and concepts that can be used to achieve high quality and continuous improvement are reviewed in (Operation Management, 2016). Additionally, issues that lead to poor quality can be identified. In quality management, there are several cost factors that need to be assessed to achieve quality. Such costs that determine good/poor quality are:

- Appraisal costs
- Prevention costs
- Failure costs (internal and external)
- Return on quality

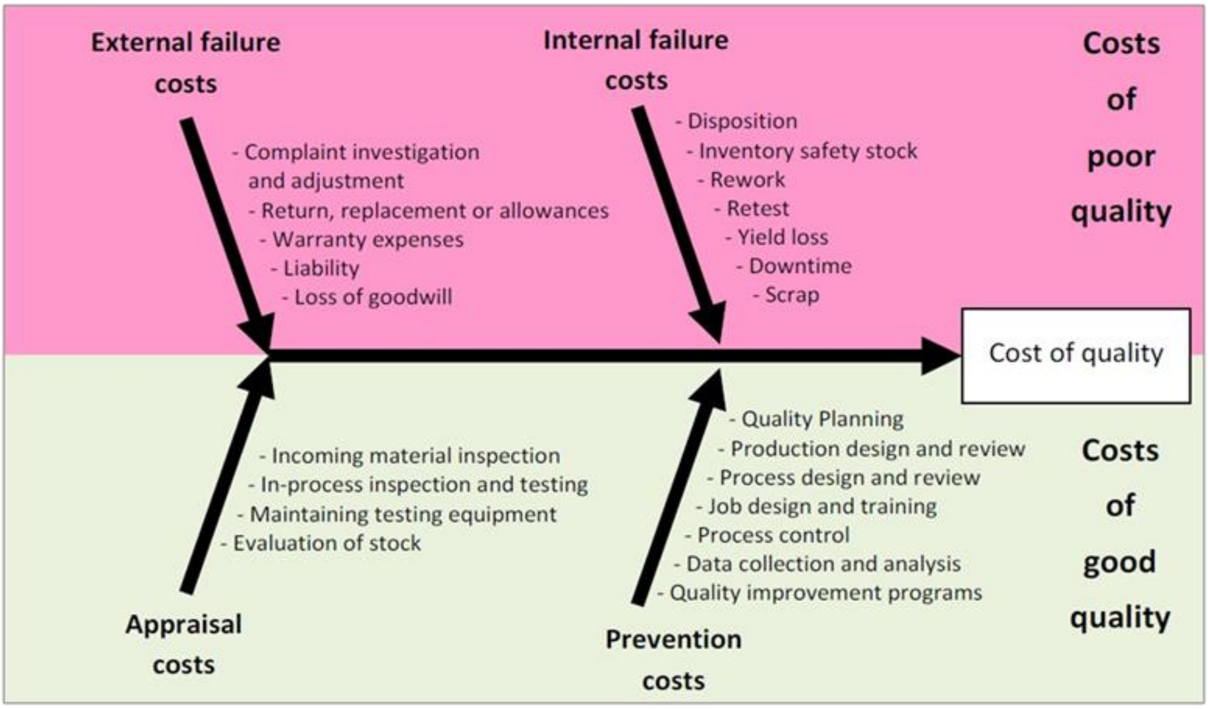

Figure 6-7 Details of Cost of Quality (Braun, 2011)

Figure 6-7 shows the list in a fishbone diagram (Ishikawa diagram). As shown below, issues such as test, inspection and evaluation are under the appraisal costs (examples: inspections, quality audits and acceptance tests) and they can prevent any problems with the product in advance. As well as prevention costs itself, that includes process related information. Examples include quality training, quality assurance, and quality planning. If these costs are not budgeted in the organisation then there is high chance that the cost of quality will need to be paid later in the process or product. The effects of failure can be internal or external, depending on the nature of the reason for poor quality product. An example for internal costs includes retest, rework, scrap, or redesign. External failure costs can be non-conformities, replacements, or defects. Failures severely damage the organisation's reputation due to delay in delivery, mistrust to the company's capability, and interdepartmental issues (production vs. sales department).

According to Giakatis et al. (2001), the problem is a lack of a systematic approach on how to deal with the cost of quality. BS 6143 Standard (Guide to the economics of quality, prevention, appraisal and failure model) was proposed to note the failure costs first. This will lead to an increase in appraisal and prevention, consequently, the increase in quality awareness in different levels of the organisation. Therefore all three costs of quality will decrease.

The recommended procedure for the simple part was to increase the engineering instructions in the work-pack. This way, the operators can better understand the procedure and increase information flow in the company. The other benefit was the recording and documentation of the engineering data for each part. This way there was less variation in the process due to change in workforce (the operator is the main cause of variation).

In order to identify the potential cost saving solutions for Helander, a meeting with manufacturing team leaders of the project (case study component – Can Cell - simple part) was arranged and a gap analysis (Table 6-6) of the Helander processes for the targeted part was undertaken. The gap analysis designed by the author was selected to show the actions and opportunities (recommendations) for each action. These recommendations were mostly targeted at the engineering team with a template from the quality department to be written by senior engineers. The Gap analysis is between the customer process requirement (column title: Process), International Standard (Column title: ISO 9001) and case study company process cycle. In the columns "Actions" and "Opportunities", the sample part does not comply with for both the customer document and the standard cycle are highlighted in green, addressing the engineering team, and those in yellow address the inspection department. Table 6-6 shows a snapshot of the gap analysis table.

Table 6-6 Gap analysis designed by the author to study on simple part

Company Gap Analysis in accordance with SAE AS9100C and requirements of ISO 9001:2008						
	Standard (subject)					
Gap	Process	ISO 9001	HP process/Procedure cross functional diagram	Sample	Actions	Opportunities
1	Company scope	1.1 General	QM - ISO 9001:2008	N/A		
2	Risk register	3.1 Risk	QM - Contract review process	No	Risk register HF3 (Quote form) does not have a guideline	Improve the risk register on quote sheet/CR
3	Quality policy (Manual)	4.1 General requirements	QM - Quality policy	N/A		
4	Document control	4.2 Documentation requirement	QM - HP1 Document control procedure	N/A		
5	Management review process	5.6 Management review	QM - Management review process HP Issue: 28 Nov 2014	N/A		
6	Resource management	6.2.2 Competence, training and awareness	HP20 Iss 4 Training, competence and awareness	N/A		
7	Contract review process	7.1 Planning & product realization	Contract review process HP Issue: 07 Apr 2015	Yes		
8	Risk management	7.1.2 Risk management	HP31 Risk management*	N/A		
9	Customer requirement	7.2.2 Review of requirement related to the product	Contract review process	No	Contract review process does not include the inspection and	Enhance the contract review process
10	Customer service	7.2.3 Customer communication	QM - HP21 Iss3 Customer assist	N/A		
11	Purchasing	7.4.1 Purchasing process	Procurement and approved supplier process 22 May 15	N/A		
12	Goods inwards inspection	7.4.3 Verification of purchased product	Goods inwards process	Yes		
13	Production engineering	7.5.1 Control of production and service provision	Production planning, scheduling and inspection requirements process	No	Operational description are not clear	Work pack instruction for operations and set up instruction to be reviewed
14	First article inspection	7.5.1.1 Production process verification	Production control HP27 Iss2 First article	No	1st Off represents for each batch	To run the FAIR and keep the records
15	Operation change request	7.5.1.2 Control of production process changes	Production Planning, Scheduling and Inspection Requirements Process	Yes		
16	Control of production	7.5.1.3 Control of production equipment, tools and software programs	HP8 Iss13 CALIB	Yes		
17	Process validation	7.5.2 Validation of processes for production and service provision	Goods inwards process (Inspection) New product development process Repeat production engineering process	N/A	1- Operators (stamp) 2- Inspection (stamp)	To review the route card for repeat parts (update) by PE
18	Traceability	7.5.3 Identification and traceability	QM - HP7 Iss4 Traceability	Yes		
19	Product handling	7.5.5 Preservation of product	QM - HP11 Iss4 Storage handling packing & despatch	Yes		
20	Calibration & monitoring	7.6 Control of monitoring and measuring equipment	HP8 Iss13 CALIB	No	Gauges are not monitored (date)	Ensure gauges date label are still valid
21	Final inspection Process analysis	8.1 Measurement, analysis and improvement	Management review process Internal auditing process	Yes		

The implementation of the proposed idea of introducing the tool sheet, setup sheet, work instructions, quality schedule, and stage drawing with selection of equipment for measurement was performed first on the simple product. A meeting was set up with manufacturing engineering team to discuss the information required for setting each machine. The idea was simply to design a complementary and easy to use form for shop-floor personnel to fill in. This form then comes back to the engineering team and, after it has been verified, it is kept as a master document for each job. This way, the information could be captured and used as a repeatable process each time the operator adjusts the machine. The tool setup form was designed and introduced to the team leaders and as a result fewer operations need to be verified by the engineering team as demonstrated in more details in Chapter 7, 7.2. The next step is to design other forms including operations sheets and quality schedule sheets.

Upon completion of the pilot study, the analysis of data on different aspects of the product showed a difference in rejection rates. The breakdown of the data in January 2015 showed that the number of items delivered by Helander was equal to 19,828 while rejection rate was 526 pieces (27 NCR[15]s raised). The 2.6% rejection rate by customers is recorded and repetitive non-conformances were nine parts for the month. These repeat non-conformant deliveries were not dealt with in detail and there were no preventative action set in place to avoid them from reoccurring. In January 2015, Helander spent the majority of its time dealing with failures due to rejections – over 65% of working hours. Workshop audits have resumed by quality department, which supports appraisal procedures, and shown that over 5% of the overall working hours were spent on rework and repair.

In order to analyse the parts, a SWOT analysis was performed to show whether there are any strengths or weaknesses with regards to developing future plans for each particular product and customer. The SWOT analysis only lists issues relevant to each other and after that the operations team needs to prioritise the tasks to improve the organisations' performance for related product. The output of the SWOT analysis is a good starting point for understanding the needs for future plans (JISC infoNet, 2015). The marketing function role is to evaluate the list of ideas against the organisations' objectives for each section. The SWOT analysis on the case study part is presented in Figure 6-8 to support the validity of the proposal. The estimated time for the manufacturing engineer to write the work instructions and attach them to the work pack was 8 hours and the hourly cost was approximately £30. If Helander spends this cost on instruction writing and ensured the documentation was complete, the timesaving's on setting the machine is 1:30 hours for the simple part. The breakdown information on the part since the beginning of the order by customer also showed the cost of quality to be about £20k. This is regardless of the administration cost and customer dissatisfaction due to delay.

[15] Non-conformance report

The SWOT analysis showed the Helander company analysis for the simple product. Research evaluation and assessment based on loss value is considered a good measure to determine what needed to be done as a preventative action. Since the key of every business is to generate capital by giving service and/or product, it was necessary to evaluate the financial benefits. For this purpose, a further more complex and typical component outlined in section 6.6 to measure the associated costs for reject and rework.

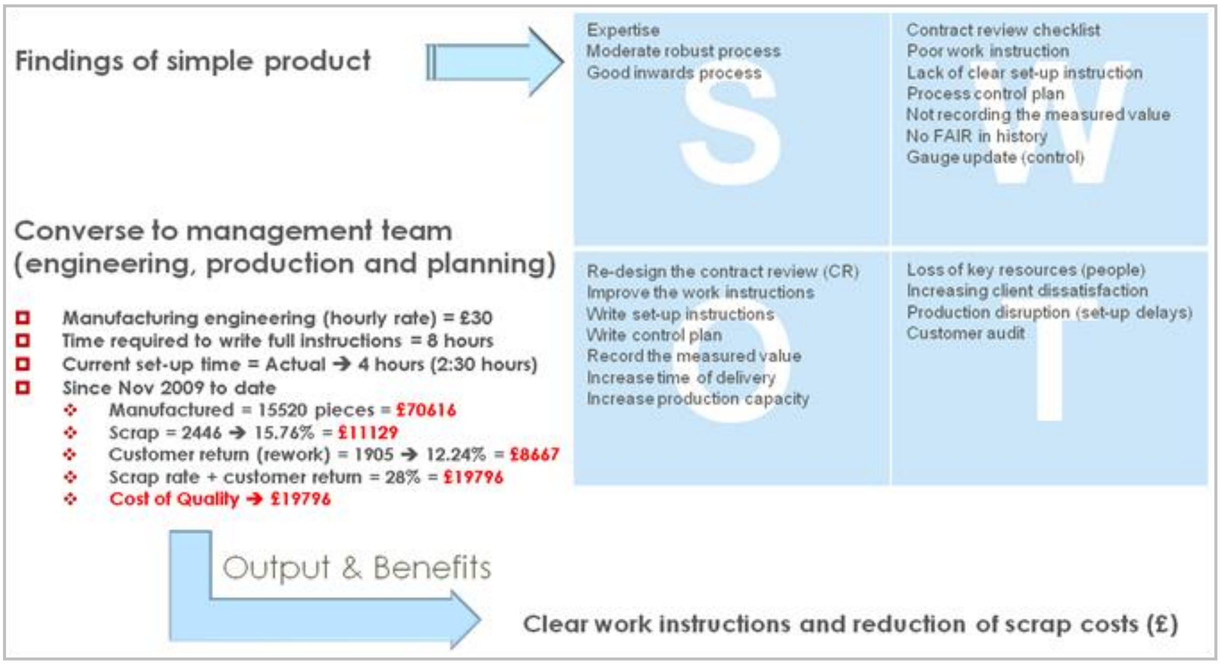

Figure 6-8 SWOT analysis and results of the study on simple part

It is shown in Figure 6-8 that the total "Cost of Quality" for this example is 28% of the overall value sold over a period of six years. The weakness section of the SWOT diagram highlights the "poor work instruction" as one of the elements that have contributed to a 28% loss. The setup time section from the work-pack indicates that it takes 2:30 hours to set-up and prepares the machine. In my observation, it took an operator approximately 4 hours to make the machine ready. The measured set-up time from my research was approximate, as the main target of this research at the time was to calculate the cost saving for each product.

6.6 Case Study of Complex Product

After reviewing the simple part and identifying the deficiencies at Helander in processes and procedures, the work for other parts became much easier as the procedure is already done on simple product case study. A complex part was selected for a second case study (Figure 6-9), which had more operations during the manufacturing stage rather than difficulty in machining. There are 18 in-house operations for the complex part and 2 subcontractors are involved. The time cycle for the part is 22 days, subject to availability of machines for planner. Compare to the simple parts there are 3 in-house operations on the route card and the lead-time is 3 days subject to availability of resources. For the simple product, the customer required almost no documentation for the part. However, there is a more detailed control stage required by the customer for complex parts. Such controls are PPAP, APQP and FAIR. Requirements for nuclear and aerospace forced Helander to train their employees in different processes. In this section the PPAP process is explained in detail as the major requirement for quality assurance purposes at Helander.

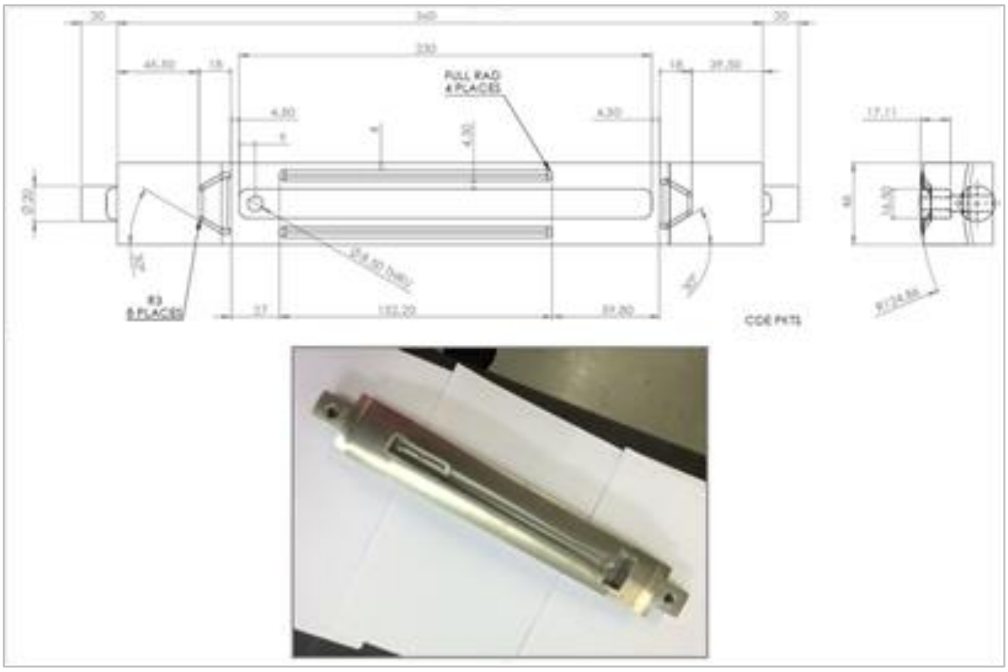

Figure 6-9 Complex part

The PPAP standardised process was first introduced by the automotive industry followed by the aerospace industry to help manufacturers and suppliers communicate and collaborate more effectively. The aim was to have control over lifecycle of the product and approve production processes before, during, and after manufacturing. According to Shrotri et al. (2014), PPAP has two purposes. The first was to provide detailed product information including design, production, and inspection process. Second was to reassure the customer that the current process was able to achieve the customer requirements and be repeatable if necessary.

PPAP has a set of elements dependent on the targeted industry. For instance, the automotive version has 21 elements that are listed in Figure 6-10. At Helander there are a set of gateways described which have better control over the process. After receiving the purchase order from customer service and checking the initial areas (scope, price, quality, and delivery) and approving all stages it then depends on the part/customer requirement if all or just a few elements of PPAP are required to be reviewed. This is because these elements may not be applicable for the targeted part/customer. In the PPAP area, the stars represent factors added by the Helander company to the initial 21 elements of PPAP. In the Gate 3 area, the selected elements are reviewed and passed to the task owners with allocated time and then PSW (Part Submission Warrant) form is completed and sent to the customer if needed as proof for PPAP.

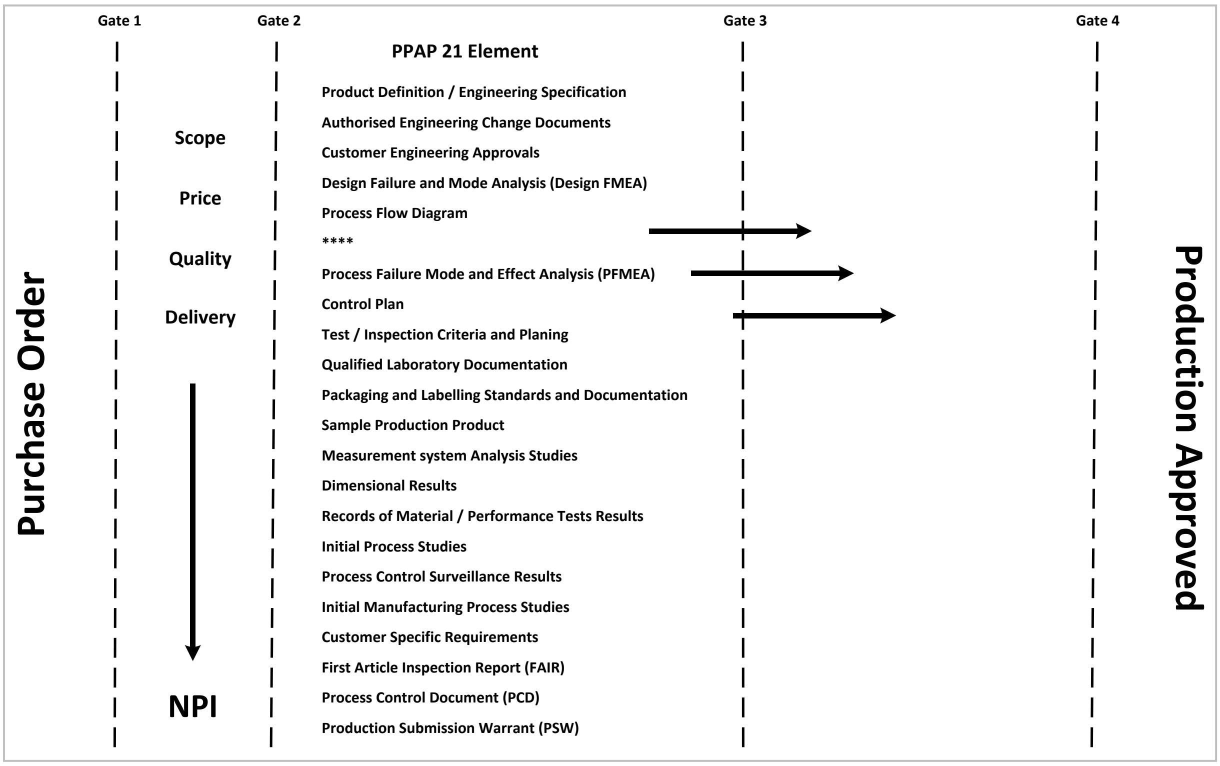

Figure 6-10 Use of PPAP

PPAP needs to be performed on NPI products, but there are also other cases where PPAP should be used. For example, a PPAP is required anytime there is a change in manufacturing on an existing part or process.

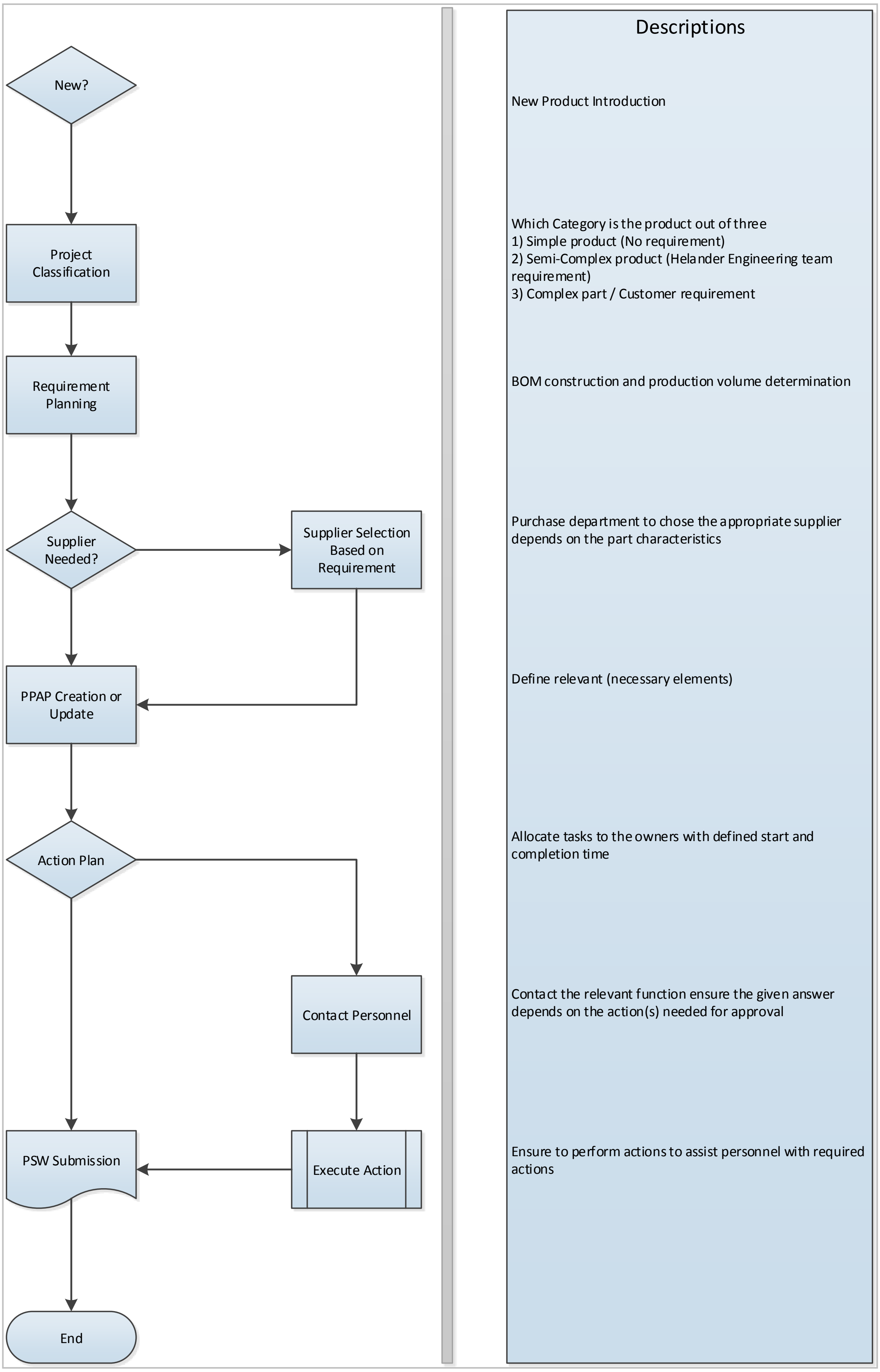

Figure 6-11 PPAP process flow used for PPAP implementation

It is therefore vital for suppliers including Helander to maintain the PPAP procedures in the quality system and develop the documents required for PPAP submission. The process flow for PPAP is shown in Figure 6-11 with explanations for each section in parallel to each area.

Use of the same process and procedure similar to simple product for manufacturing complex parts shows[16] the effectiveness of the approach over the traditional method at Helander. As shown in Figure 6-12, there are different templates being used for machine set up. These work instructions were written by team leaders or machine operators and can be followed by themselves only. These new procedures and documentations will reduce Helander's flexibility to keep their staff and reduce manufacturing capability due to dependency on employees.

Figure 6-12 Variations in machine set up document between different team leaders[17]

As part of the standardising the processes in project a set of templates were developed for the manufacturing work pack that used for simple and complex parts which can be seen in Appendix 4. By standardising the forms and drawing the workflows, Helander staffs were able to follow the procedures in a consistent way and as a result, the whole process/product will have less variation. In addition,

[16] Note: The image resolution is reduced on purpose due to data protection.

[17] Note: The image resolution is reduced on purpose due to data protection. The aim is to show the variety in formats.

instructions will be more clear and easy to follow by operators in the way that the process engineer and manufacturing team leader intended it to be carried out.

The fundamental point of the manufacturing businesses is the digital management and IT. Nowadays due to the emergence of various tools and technologies to support different stages of services and the product lifecycle, there is a high volume of information related to products from concept to disposal within the production stage. Obviously, problems in the scope of product lifecycle such as capturing, retrieving, classifying, interpreting, monitoring, and managing the high volume of existing information is essential in manufacturing. In contrast, Helander's expansion and development into a new market requires adaptation of the current tools to IT infrastructure, operators' capabilities, and also customer services department in order to become successful in lifecycle management of the product (Chbeir and Badr, 2008). One tool that is used to support the management of data is balloon drawing. Conventionally, the engineers should balloon the drawing (writing information about size for quality assurance purposes) by editing the drawing in CAD software or in PDF files. However, with evolving software solutions to aid in ballooning and referencing the metadata to dimensions it is possible to see all information for MSA on one screen. This enables operators to verify parts at the right time and at the right frequency check. It is possible to generate reports for customers as proof of conformity.

Shown in Figure 6-13 drawing (No. 1) is the conventional ballooning method that started to be used at Helander after the suggestion was made early in early stage of this project. With the use of the proposed software[18] at Helander, the speed of drawing ballooning increased dramatically with fewer errors following the transformation from manual typing to digital balloons. In the next section by selecting the balloon number (No. 2) the prompt window shows the detailed information relating to MSA will appear (No. 3).

The final results on the complex part show the potential financial savings for that particular part if the documentation is completed as proposed. Using the same principle used for the simple product for complex parts shows (Figure 6-14) the amount of £174,342 for the cost of quality since November 2011, the start of the

[18] http://www.ipi-solutions.com/

project by Helander. It is wise to say half of the money spent due to quality issues could be saved by clear work instructions. It was found that almost 20% of customer returned parts were due to repeat errors, but the lack of CAPA (corrective and preventive actions) contributed a substantial amount to the cost of quality. The SWOT analysis highlights the potential savings, which is similar to the simple part analysis as they are from the same company.

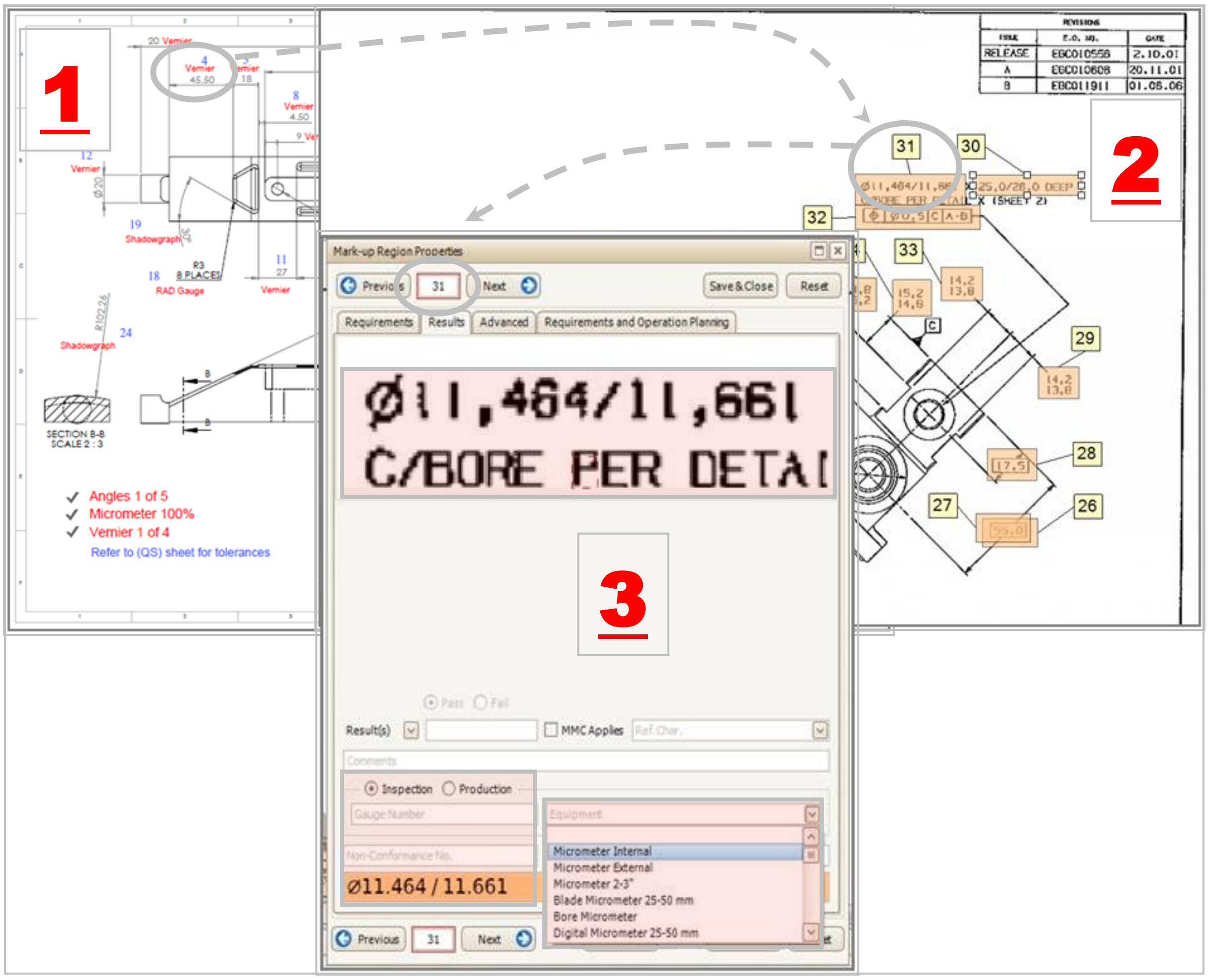

Figure 6-13 Proposed solution for ballooning and using integrated process improvement

Suggestions that are made for corrective and preventive actions (CAPA) based on the financial saving results will increase Helander's awareness in the cost of quality. In the reviewing process, visits were arranged to key customer inspection departments to understand their standards and accreditation processes. The key attributes of the parts and design intent of each element of product were captured after liaising with the customer inspection department. It is believed that lack of communication between Helander and the customer inspection department as the gateway for acceptance or rejection of the parts which had a huge negative effect on company relationships. The quick mitigation solution in this case was to write a work instruction for deburring and cleaning operations as the major non-conformances were down to attributes rather than key characteristics (dimensions) of the product.

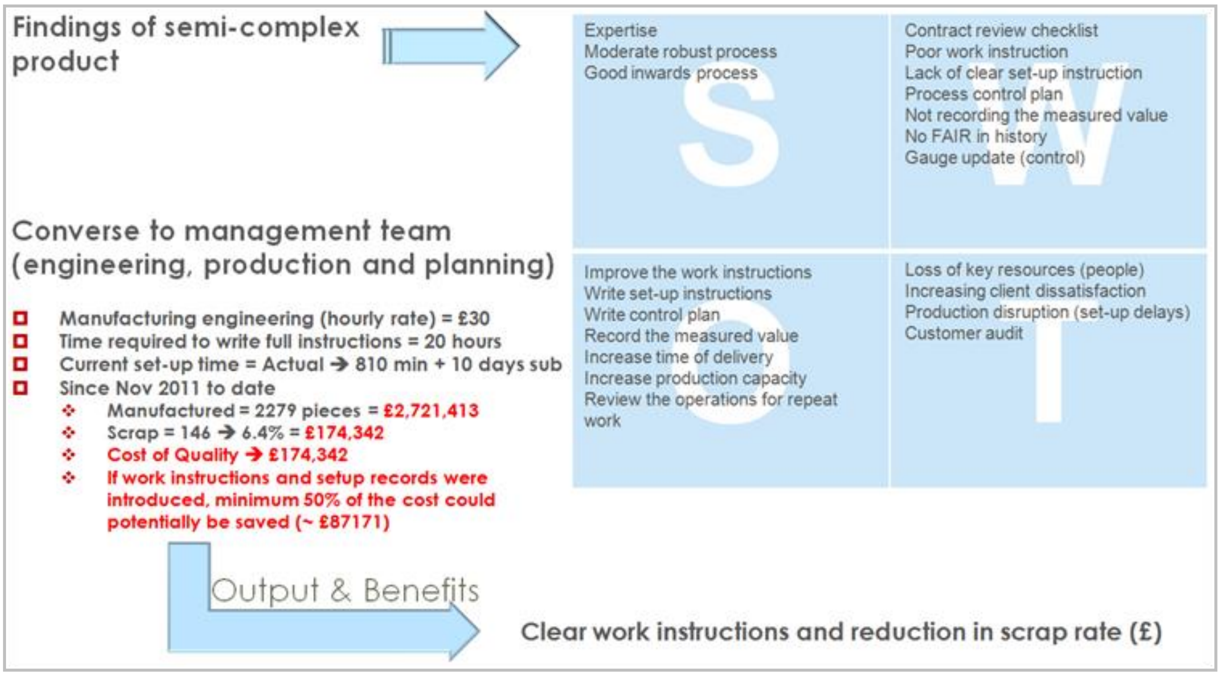

Figure 6-14 SWOT analysis and results of the study on complex part

At the end of each study, the compliance and deviation matrix and gap analysis were produced to highlight the non-conformances of the processes and suggestions that can be made. This will lead to reducing the concessions rate at Helander that can be the product of non-conformances in manufacturing. It seems that to date, the quality management system was incapable of addressing non-conformances within the organisation or procedures were not followed by staff to address non-conformances. In the next chapter the process map and links to quality department explained to address this issue. The action recommended to Helander's management team is to increase the planning resources in order to reduce the scrap cost. For instance, in the complex part example it is shown that 8 hours of an engineer's time, which costs the company approximately £240, to write the work instruction and step-by-step set-up instructions can substantially decrease the cost of quality issues and reduce the scrap, return and reject rate in general.

Chapter Seven: Control of Helander's Manufacturing Processes

7.1 Introduction

This chapter explains the existing methodology for manufacturing process control that has been implemented at Helander which has operated for almost 40 years. Helander recently expanded by opening two new sites to supply different industrial sectors (aerospace and nuclear). In the meantime processes and data infrastructures have not been improved in order to meet the expansion of the business. This chapter outlines the overall method for re-engineering of manufacturing and verification processes and presents the findings of process failure which showcases the advantages of implementing the new and modified processes and documentations. Increasing the visibilities of the processes and procedures and putting clear guidelines and uniform documentation across the company in place facilitates the manufacturing operation. This is also helps to put corrective and preventative actions in place where needed.

7.2 Process Control for Manufacturing (Helander)

Due to the lack of defined guidelines for writing operation route procedures at Helander, the manufacturing route cards tend to be incomplete and very brief. Most of the know-how for different operations is implicit and exists with experienced engineers at Helander. The main reason is the lack of time devoted by manufacturing engineers to writing instructions in support of each operation. Therefore information is passed verbally which brings ambiguity in operational procedures across different teams. For instance, one team leader refers to the CNC operation program to explain to the machine operators which steps they need to follow. Whereas, another team leader was using a hand written procedure explaining the set up and working procedure with no version control and reference to quality and engineering department documents. This inconsistency in operational procedures combined with insufficient information for supporting the operation plan causes variations in the product, resulting in high NCRs for quality reasons. On many occasions, parts have been returned due to non-conformities, such as missing features or wrong attributes. An example of a missing feature would be a form missing and a 'wrong attribute' refers to cleanliness, burred edge and/or a simple packaging instruction. These fundamental issues can have a huge impact on product performance and whether it is accepted as fit-for-purpose, yet it can be viewed as insignificant in the eyes of the shop-floor employees. Regardless of how much time was spent on machining operation or how accurate the most challenging section of the part is, a simple form shaping can cause significant problems for a customer. Figure 7-1 illustrates the inspection failure for an error in welding the pin in the right position.

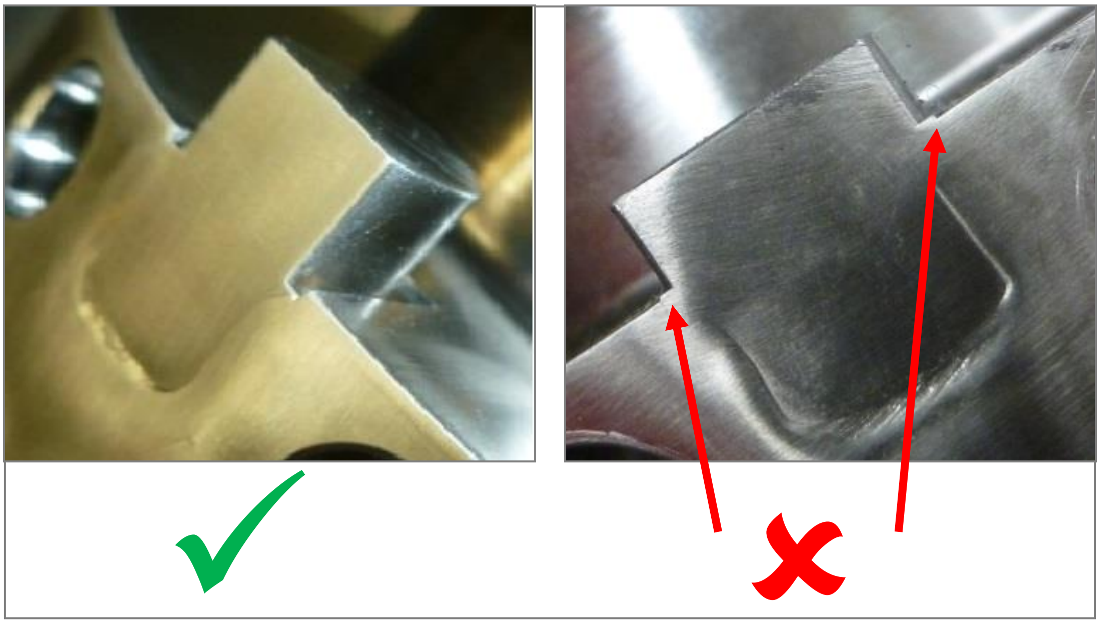

Figure 7-1 Check the pin is in the correct position and ensure the pin is not welded over the slot also ensuring the internal side of the pin is under flush (left image) or flush. The right hand image is over flush and therefore a reject part.

Figure 7-2 shows an example where a hole, functions as a pathway for wires connecting to electrical features of a drive shaft and sharp edges on the drilled hole can cut the wire while the component is in oilfield in operation. This issue can affect business trust which can takes years to re-build. In precision industries, it is believed that a problem with quality issues speaks louder than issues of late delivery or pricing due to cost of repair and damage to the overall project.

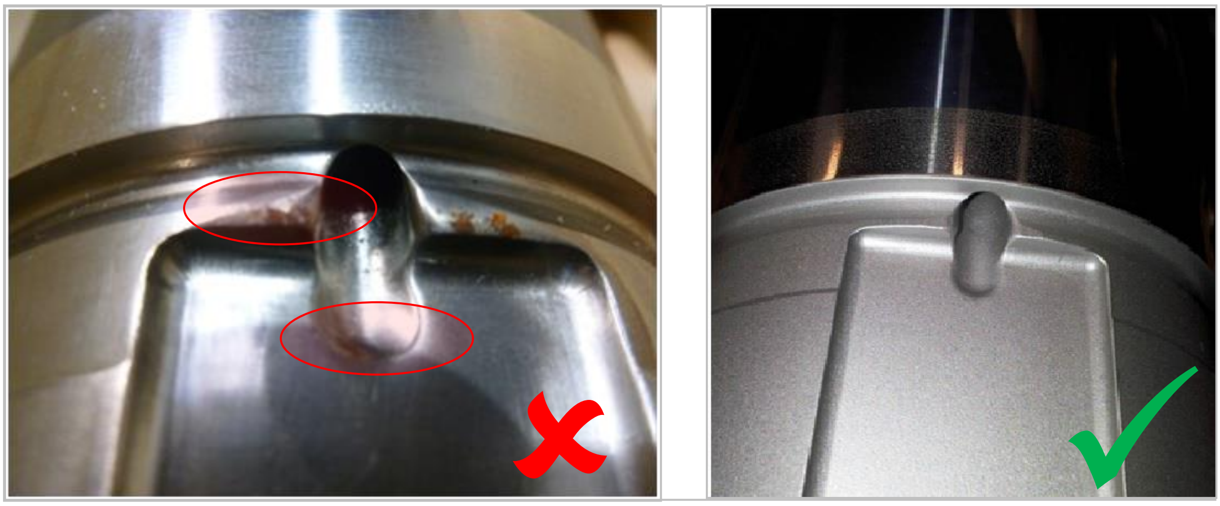

Figure 7-2 Example of poor forming and acceptable form finishing on Helander parts (Marked edges are not formed to customer specification)

The other criticism is lack of existence of a solid tracking system for operational procedures due to the lack of ownership across different procedures. It seems that MRP (Manufacturing Resource Planning) systems and access control in different areas are not understood by many SMEs. This issue enables almost everyone with username and password to MRP system to have a privilege to modify the descriptions on operations. As a result, change in processes and procedures are not managed correctly. For example, the quality department receives out of tolerance components and it is their duty to notify the production and manufacturing department regarding non-conformities. Since many communications take place orally, information is not recorded in the right format and it is difficult, if not impossible, for the quality department to manage the change in procedures. In one instance, a customer raised the same non-conformance issue four times in a year. This by itself is proof that there is no corrective and preventive (CAPA) procedure in place. This issue not only causes the manufacturing company to waste resources due to rework, but it affects the reputation of the business. Additionally, the customer feels ignored by their supply chain and there is an increased risk that the customer will take their future business to competitors.

The majority of errors in manufacturing are due to inconsistencies and failures in process steps and setting up instructions on machines. Other contributing factor includes faulty machine operation, adjustment errors, setup errors, or selection of wrong tool/tool holder for specific operations. Documenting the operations and processes can be introduced in manufacturing procedures to reduce these ambiguities. Operators with different skill levels and experience should be able to follow the methods outlined on the process documents. Each operation should have an SOP, work instruction (visual if necessary) and other supporting documents (i.e. images). Minimising the variations in final product can only happen if the manufacturing process clearly addresses all necessary details for shop-floor operators. The flow of information in SMEs should be developed in a way that allows only the senior engineers to design work instructions. Currently, the shop-floor operators and team leaders are troubleshooting operational problems by firefighting or reactive methods. The process of having such a system starts right from the point when the company wins an order and the work order is about to be sent to the shop-floor. The process of re-engineering the operations procedures requires a holistic approach that involves change of current company culture and providing detailed information to operators rather than verbally transferring the information via senior engineers on the shop floor. Once the information is transferred using job cards, the next step is to follow the instructions and machine the work-piece. Here the operator is responsible and the owner of the process and any quality issues arising. The operator will be in charge of taking actions accordingly based on defined methods. With this method it is possible to deliver an attractive task with clear instructions to operators which will allow them to complete tasks with a high level of quality. By adopting this systematic approach it is possible to get feedback (if any) from operators, feed the information back to the engineering department and control changes based on traceable documents in the MRP system. This process seems to be obvious in manufacturing environment and might be expected to appear in ISO standards. The main reason that these processes are not part of ISO certification is that the details of the operation procedures are not believed to be important. There is also a lack of commitment to change company procedures to address this issue.

Differences in communications have resulted in gaps in data transformation within the organisation. An example is the transfer of know-how from the last generation of engineers to the next generation of engineers. Knowledge use and reuse in advanced manufacturing technology enables engineers to improve speed and productivity with a higher level of confidence. However, Pahl et al. (1988) claimed that 80% of new designs are from reused knowledge, whereas research by Ettlie and Kubarek in 2008 showed that only 28% of new designs are from reused knowledge. Reed et al. (2010) reported that the application of advanced manufacturing techniques reduces errors and increases product familiarity for staff while maintaining product consistency levels.

Helander has identified that capturing and reviewing data and documenting information for different processes is key factor in sustaining the business. Therefore Helander decided to define the process in order to re-engineer the manufacturing procedures and format them into a data-store so that any operator with sufficient knowledge of CNC machining could perform the task by using the relevant component route cards. Other achievements would be to reduce the time taken for new staff to adapt to company procedures and to help the company maintain the quality in manufactured products.

It was decided to give the ownership of the process control documents to engineering team leaders. These instructions need to be explained in detail and accompanied by the CAD models and stage drawings if required for CNC machine operations. At first glance, this appears to require a remarkable effort from team leaders to configure such a system for every single operation. To reduce the effort for the team and have a consistent method, a template for each document is introduced and supplied to the current operators for completion. This template replaces the documents that each team leader generated for themselves to control the machine setup procedure (Figure 7-3). Team leaders are then required to review and edit instructions rather than writing procedures from scratch. This idea speeds up the documentation process and eliminates the time required for process engineers to write-up all the procedures. Reference numbers are stored in the databases and are assigned to every work instruction and SOP (standard operating procedure). The reference number can be found on the operations route card and can be cross-referenced to the right document for performing specific tasks. The operation can be as complex as CNC machining or as simple as de-burring, washing or even providing packing instructions. All of them have a unique reference number that can be found both in manufacturing route cards and Helander's main manufacturing repository file. As long as there is documented know-how available, errors can be minimised. Sample templates of different documents required for typical operation can be found in Appendix 4.

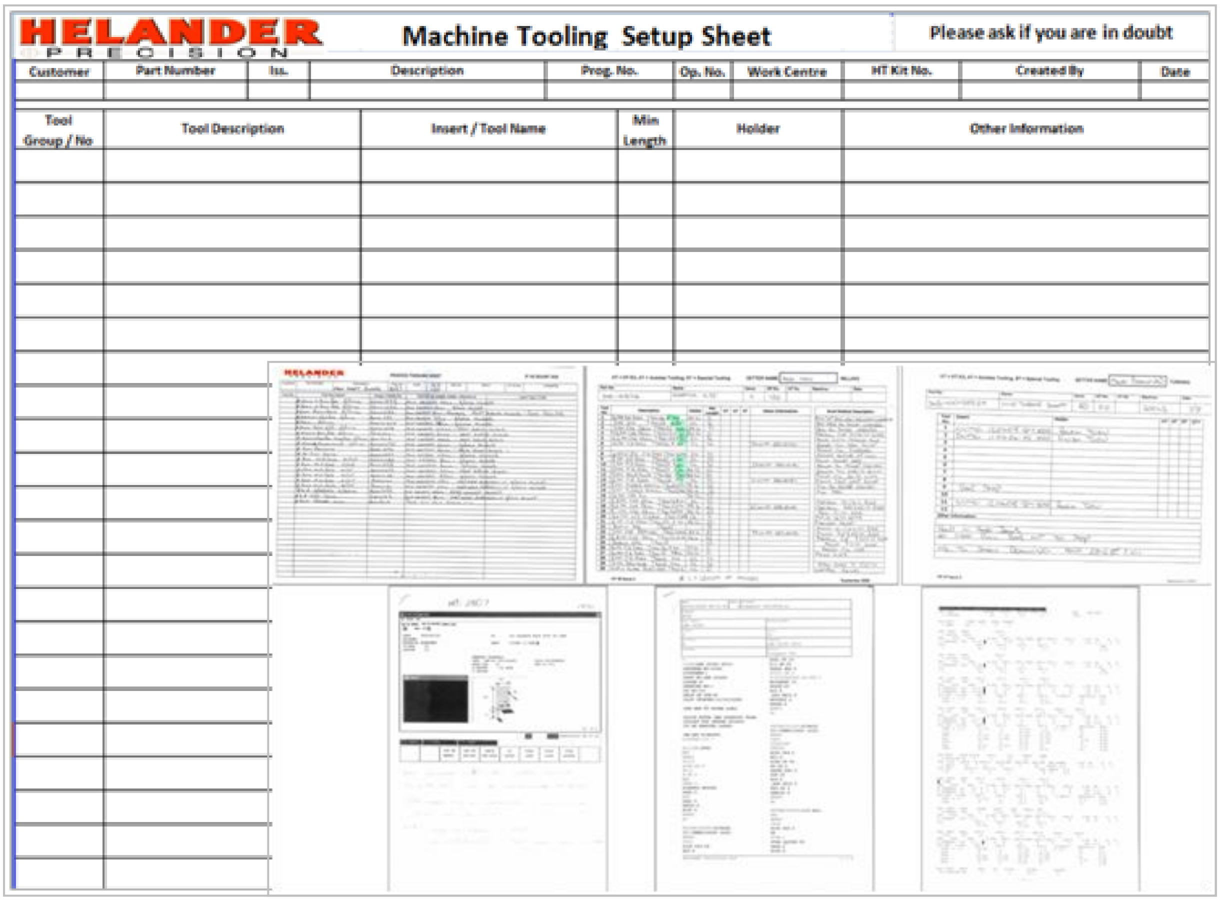

Figure 7-3 Generating forms to support operations and machine setups

7.3 Review of Existing Manufacturing Process

Gunasekaran and Ngai (2007) argued that efficient management of product information is the key to enhancing an organisation's competitiveness. In order to understand the current processes at Helander, the flow of information in the whole product lifecycle was re-evaluated. A review of Helander's current processes at an early stage for "requests for quotation" (RFQ) revealed that the workflow followed different routes dependant on customer requirements. This is due to the variations in standards requirements and sensitivity of jobs from different customers. In the case of standard (repeat) products the production route is well established and there is little room for improvement but SMEs more often manufacture short runs of bespoke products. However new products go through a NPI process which depends on the customer requirement which can be time intensive and requires more documentations and certificates.

At Helander, most of the orders are created by customers for specific application. These processes known as "engineering to order" or "make to order" are time intensive for experienced engineers to quote Kingsman and de Souza (1997). This is due to the variations in required standards and sensitivity of jobs from different customers. For instance, orders from the nuclear industry are reviewed in detail by the quality department to ensure all relevant requirements are fully considered. RFQ is reviewed by an estimator based on their area of expertise. Using the company standard cost estimation spreadsheet, a cost sheet for every stage of the job is issued. At this stage, the estimated cost of different operations, sub-contract processes, and man-hours are reviewed and added to a burden rate. The burden rate is a constant ratio from the finance department that entails the inventory, machinery and employee costs. This is a conventional method of cost analysis for many SMEs, which are not big enough to procure high tech software for cost estimation. It has been argued that although this method is reasonably accurate, it takes significant time away from qualified personnel for quote generation rather than value adding activities such as process improvement (García-Crespo, 2011). Other criticisms, such as risk inaccuracy, time consuming processes and late quote response, are not covered here as they are outside of the scope of this research.

In the next stage, if the customer agrees on the quoted price, then they will place the purchase order. The order goes under engineering contract review to plan the best method of manufacturing. At this stage, depending on the complexity of the job, a cross-functional team determines the operations order. Typical members of the team include the original estimator, senior manufacturing engineer, manufacturing team leader, purchasing department representative, customer service representative, quality manager and production planner. Zhao et al. (2011) argue that from a measurement point of view, process planning can be divided into two categories:

- Micro level, includes the machine program, inspection program, and motion commands
- Macro level, more generic decisions need to be made which include choice of the machine tool based on tolerance of the part, desired uncertainties and the question of when and what to measure on key performance metrics to ensure the process is under control

SMEs seem to undertake a more in-depth review at the micro-level, as this is a requirement of the component production process. The verification and validation of the manufactured parts in different stages is the key element to be discussed here. Macro decisions are of greater importance but also less focused in many SMEs, mainly due to lack of time and resources. The area that Helander is focusing on to improve accuracy and productivity is to have everything in plan prior to manufacturing. For example it often happens that a part is manufactured in operations 10, 20 and 30 with no problem. Then operation 40 requires a fixture or specially designed tool which is not prepared in time. The knock on effect of re-planting by production team can cause problems on other opportunities Helander might have. Such problems includes failure in production planning, delay in overall delivery and the payment of a penalty premium to subcontractors to prepare the tool or use other machine capacity and reschedule their work.

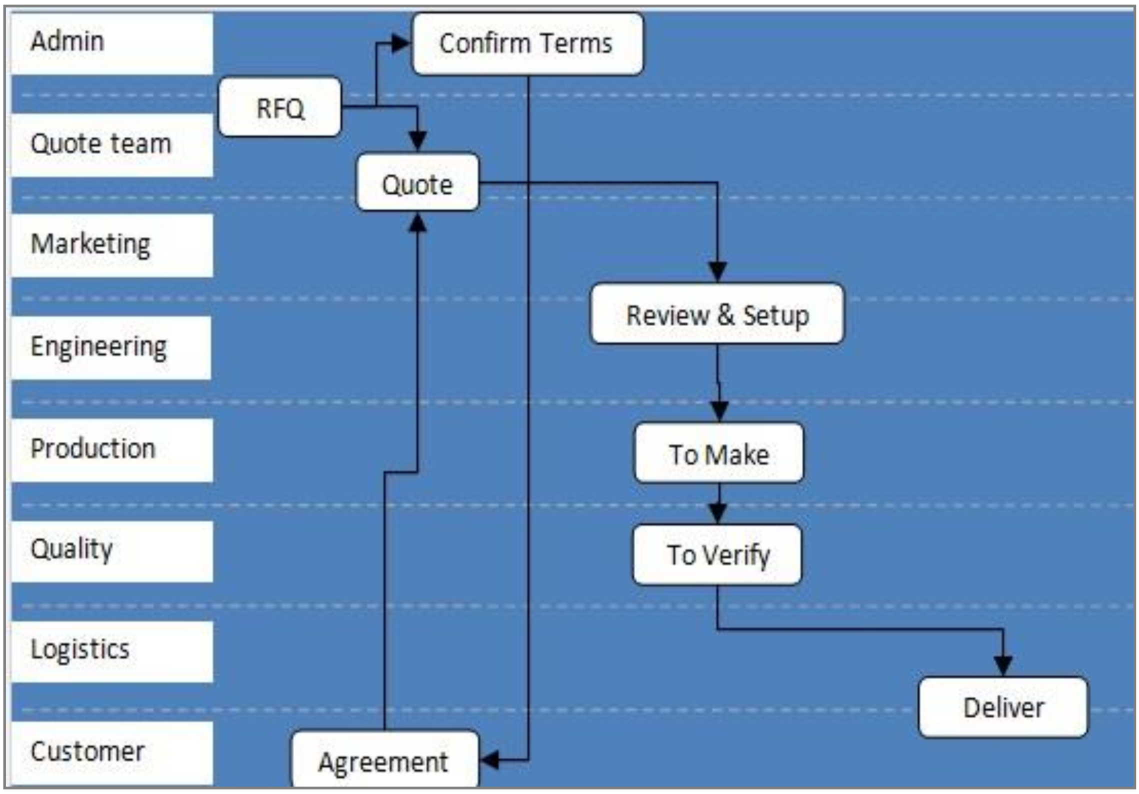

Figure 7- 4 Simplified process flow within an SME

At the next stage, team members agree on a plan and the component is passed to the production department to plan activities and notify the delivery date to customer. After receiving the RFQ (Request of Quotation) form customer and ensure the part is quoted correctly and terms and conditions are within the company's scope in conjunction with the *Manufacturing Team Leader*, the *Manufacturing Manager* closely monitors the component at different stages of production to ensure high quality of the component. As shown in Figure 7- 4, the simplified big picture of the procedure illustrates when parts are made and the verification process is undertaken by the quality (inspection) department. There is a risk of failure (producing scrap components) due to the lack of a simultaneous verification system to perform on-line checking while components are made on the machines using this model. The operations procedure is initially written by manufacturing team leaders. At this stage, if the components have not been made before, the operating procedure undergoes multiple revisions until the best method is found and the process passes the FAIR (first article inspection report) stage. It is again the team leaders and manufacturing engineers who validate and ensure that the right method is recorded.

The overall map of the Helander company and procedures is shown in the format of tube map. The idea of using a tube map was proposed by a quality manager suggesting that this map is more easily understood by individuals at different levels and by teams at Helander. Legends used for the tube map in Figure 7-5 are self-descriptive and each colour shows the different functions of the teams at Helander. Functions in here are referring to different personnel for specific roles. The roadmap is only used as a general guideline to show the flow of information and documents. Documents should be with the component in the shop floor during the manufacturing operation.

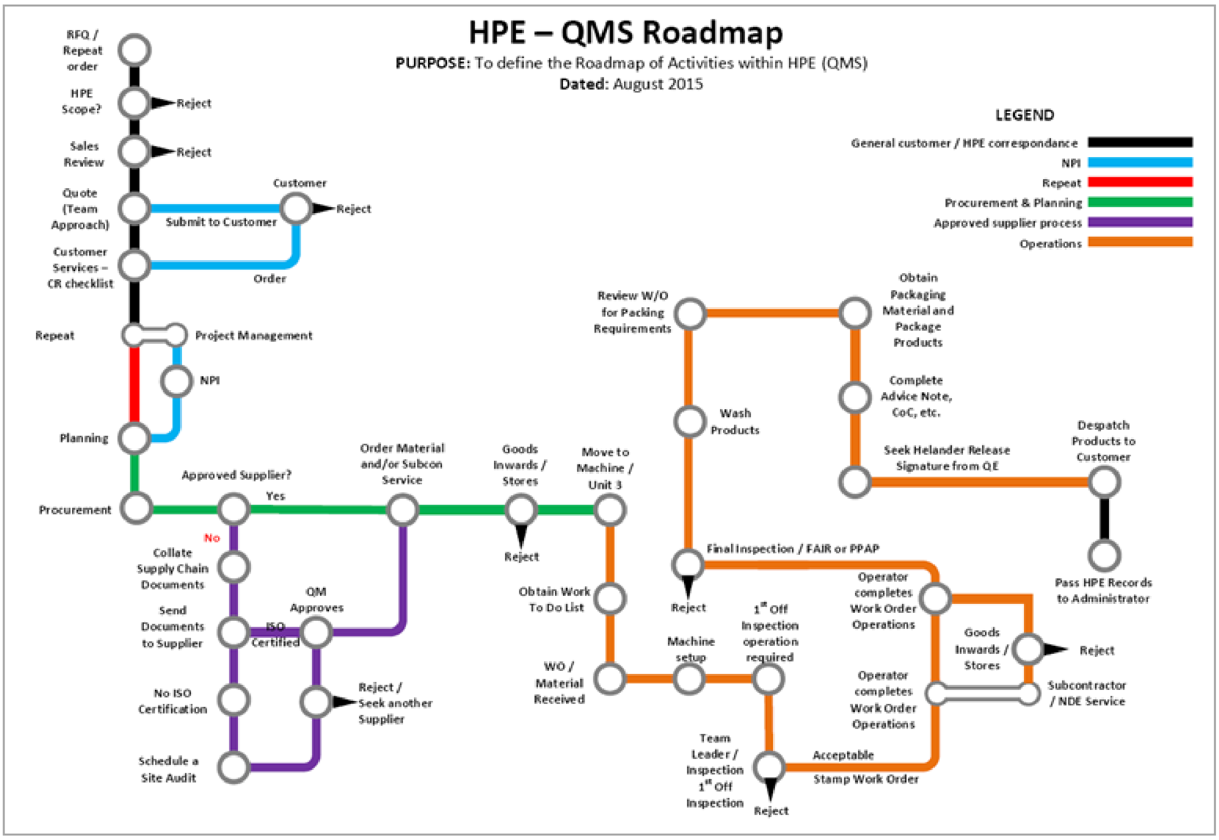

Figure 7-5 Tube map of HPE (Helander Precision Engineering)

7.4 Development and Implementation of Manufacturing Re-engineering Procedure

In today's modern manufacturing industry there is an increasing need to improve internal processes to meet diverse client needs. Process re-engineering is an important activity, but the re-engineering procedure rate in SME level is very little. Business pressures shift the focus of SMEs toward winning new projects and contracts rather than developing long-term, sustainable manufacturing processes. Variations in manufacturing processes are inevitable, but the amount of non-conformities often exceeds acceptable levels. This section is focused on the re-engineering of the manufacturing and verification procedures for discrete parts production with the aim of enhancing process control and product verification.

The ideologies of the 'Push' and 'Pull' approaches to manufacturing are useful in the context of process re-engineering for data improvement. Currently information is pulled from the market and prominent customers, and manufacturing companies try to (Push) make the right product by following customer procedures that attempt to verify against specifications. This approach can result in significant quality control challenges. It is important to re-engineer processes and product verification in SME manufacturing companies as they have a higher tendency to remain static in contrast to the changing pace of technology. Leadership, culture, ownership and process management are among the main attributes required for the successful deployment of process re-engineering.

SMEs can be reluctant to adopt new techniques in their processes and procedures. In SMEs, conventional methods are more popular because these methods are well established. As technology moves on, these companies ignore spending on research and development (R&D), primarily due to lack of resources. The lacks of investment in R&D lead to a lack of competitiveness and also problems in both quality and lead time. One example is that SMEs frequently under-perform when quoting. It is mainly because the quotation is done manually and relevant correspondence is saved by different team members. Quoting software (knowledge based system) has been introduced into Helander and it helps to treat all orders in the same way. This eliminates issues of bias and personal experience which might arise across different engineers. All relevant files relevant to each order and customer are saved and maintained within the company regardless of who worked on them (García-Crespo, 2011).

There are various tools and techniques which exist to put company policy into practice. Various bespoke services must be evolved in order to apply procedures at SMEs in a successful manner. Besides, the working environment should facilitate the concept of continuous improvement. This is only possible if TQM[19] is supported by key management functions such as people, processes and systems in the organisation.

At Helander company, different methods are applied in parallel. There is Plan, Do, Check, Action (PDCA) for interdepartmental processes that are reviewed for different procedures. In parallel to this, the processes are mapped in cross-functional charts for different departments showing the flow of documents and data. These cross-functional charts show the bigger picture of interdepartmental procedures and enable the managers and team leaders to see the opportunities for improvement. The other method that is used at Helander is to give training to staff and promote awareness to employees. Employees are educated by the quality department to raise issues on the format of non-conformities and make problem solving more comprehensive, rather than fire-fighting, reducing chaos in the organisation. It is vital to the company that employees know what the true requirements are to deliver their tasks and whether or not they have the capability to meet those expectations consistently. Therefore, the workflow should clearly define the procedures so that everyone knows their internal and external customer. If any non-conformity occurs in the workflows or procedures, it is the primary task of the affected person or team to raise a non-conformance report to the quality team. Later on, the quality team will modify the workflow in a way to prevent the scenario from reoccurring. A sample of the workflow in the format of the cross functional diagram is shown and explained in Figure 7-6. The chart is designed to be used as a reference of workflow between different functions of the organisation. So often, even employees with experience in their role pass information to the wrong people in the organisation and expect results back within a fixed timescale. Obviously the wrong people cannot answer the need and due to their workload or their competency and interest they will not notify the right people to deal with the requested information. This scenario will cause delay in the process and can

[19] Total Quality Management (TQM) is a structured approach to companies to improve the quality of products and services through responses to their continuous feedback (Rouse, 2016).

have an impact in the shape of producing non-conformant component. In order to avoid these situations the workflow explains clearly what form to be used and who is responsible for different actions. These series of charts are versions controlled in the Helander Quality System and owned by the quality department.

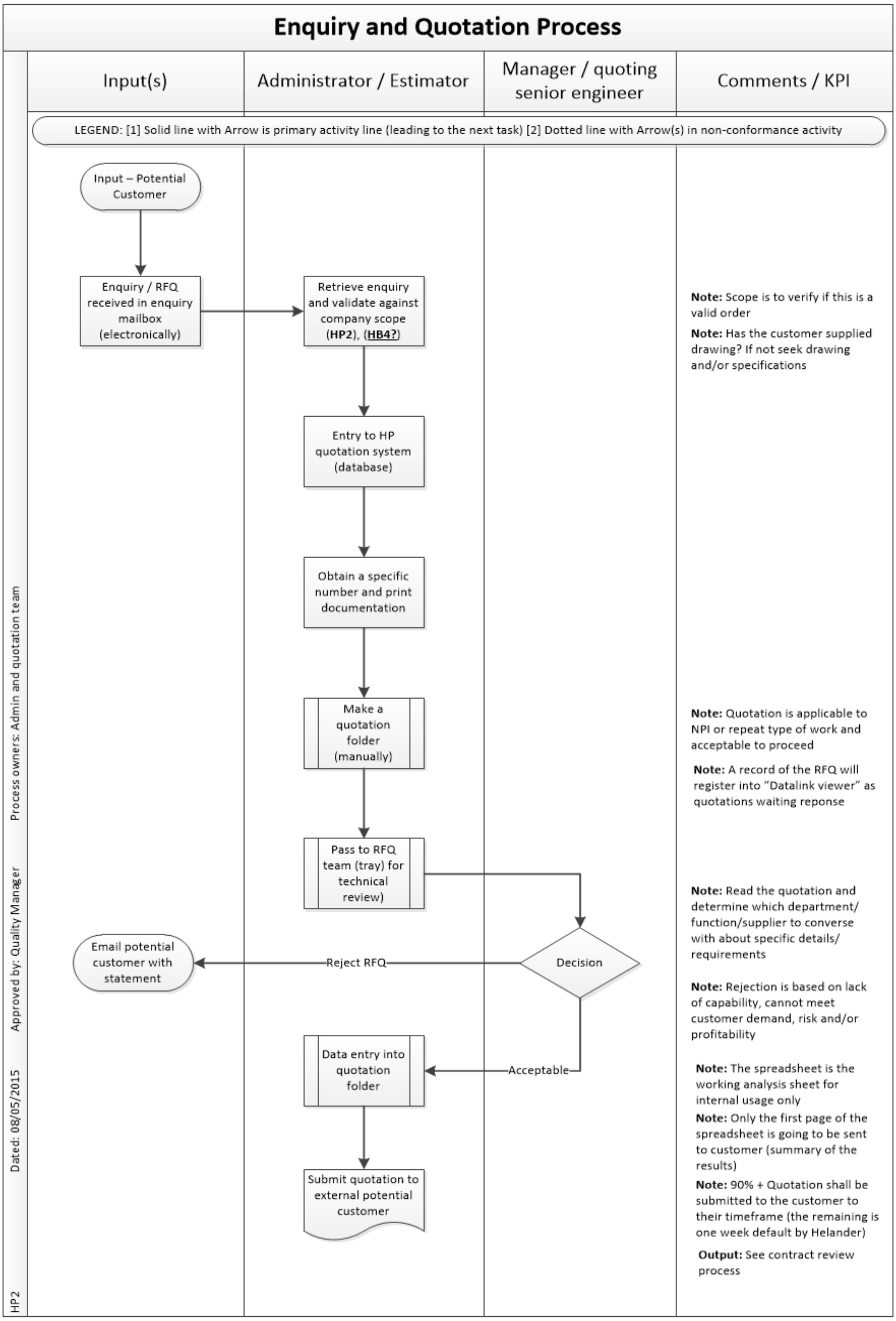

Figure 7-6 Cross functional diagram shows the interactions between enquiry and quotation process

The author's contribution to the SME case study is to show the importance of standardized forms for operations in (section 7.2). It is explained that the vitality of the implementation of standard operating procedure in the shop floor in order to have uniform documents and processes across the company which increases personnel's understanding of parts and operations (section 7.2). This will help Helander to have a more consistent process in manufacturing which can increase the chance of repeatability in manufacturing.

Also the general visual guides designed for different parts show the forms of pass and reject for each product. This was used as a clear guideline (section 7.4) to prevent manufacturing of out of specification products at the inspection stage rather than at the customer.

The other work done by the author is showing the organisation chart in different formats that can be understood by employees with different backgrounds across the shop floor. It also shows the procedures in visual format to facilitate the interpretation of communication between different departments (section 7.2).

Chapter Eight: Performance Measurement of Helander Machine Tools

8.1 Introduction

Manufacturing industries rely on machine tools such as CNC, milling, turning, and grinding machines. The quality of finished products is closely linked to machine tool quality. The quality and accuracy of machine tools can be defined by measuring repeatability in machine tool positioning. Prakosa et al. (2011) explain that high accuracy refers to process repeatability while precision refers to degree of conformity to its exact value. Five axis machines are becoming more popular as customers demand parts that are more complex. In high value manufacturing, the importance of machine tools to produce high accuracy products is essential. High accuracy is defined by producing parts in a repeatable manner and ensuring precision in compliance to the defined value in the part drawing.

The performance of the machines is often affected by positional errors. Causes can be related to incorrect tool offset and incorrect centres of rotation. Such errors can also be the result of thermal expansion, machine setups and/or collisions between the tool and part. Consequently, it can be difficult to produce highly accurate parts consistently. It is therefore necessary to ensure machine tools are tested for positioning accuracy. Often SMEs have to ignore such factors due to extreme limitations in resources and time. In other instances, companies have the measurement system but it is not utilised due to the skills required and complexity of the procedure. On the other hand SMEs routinely use sub-contractors for highly complex work. There is a requirement for rapid improvement in the effectiveness of the supply chains with support from downstream companies who might perform functions such as welding and coating. Some benefits of machine tool verification are listed below based on observations at Helander:

- Improvement in machine tool accuracy (by adjustments in machine tools)
- Decrease in set up time (by undertaking a defined set up procedure rather than ad hoc processes)
- Confidence in process capability (by reducing uncertainty and repeated measurements)
- Reduction in errors (by reducing the risks in manufacturing)
- Interference prevention between tool and the workpiece (by adjusting the tool at certain intervals)

8.2 Benefits of Regular Machine Checking

Regular machine checks will help to improve the overall equipment efficiency and reduce waste with commensurate cost saving. Some of the main benefits and savings in regular machine tool verification are as follows:

- The machine's capability for producing parts to tolerance is understood.
- Scrap / rework caused by machine errors are greatly reduced.
- Prior 'value added' activities are safeguarded by choosing accurate machines for further machining.
- Touch probes for job set up tasks are utilised.
- Production schedules are more accurate based on performance capabilities.
- Throughput is increased by optimising feed rate performance.
- It is possible to evaluate one machine against another (existing machines or machines the user is thinking of buying).
- Investment in new or used machine tools can now be 'signed off' after the equipment has been checked.
- Profit increase by reducing maintenance and downtime in machinery
- When companies are choosing subcontractors such as Helander, the subcontractor can confidently demonstrate the machine's accuracy.
- By removing uncertainties about the performance of machines, conflicts between production, quality and maintenance departments are minimised.
- Getting the best out of existing machines means they will be more accurate for longer period. It is likely to postpone the need for new machinery.
- Performance can be checked before blaming the machine and automatically calling maintenance division of the company (It may not be needed at all).

- Regular machine tool verification is an essential process / pre-requisite when implementing a preventative maintenance programme with minimal manpower.
- Verification helps to examine performance trends, helping to predict (and thus prevent) major machine tool breakdowns.
- Results can be archived to provide a traceable history of the performance of each machine.
- Management can make better informed decisions regarding which machines require priority attention and those that need replacement.
- The information helps to reduce the number of breakdowns, therefore reduces pressure on machine tool maintenance resources.
- The best possible performance out of machines can be achieved, irrespective of age or condition.
- Inspection failures can be reduced by improving the processes.
- The capability of the process can be proved without the need for lengthy investigations.
- Deterioration in performance over time can be detected by historical review and be used to schedule maintenance work prior to machine breakdown.

This list is indicative of the considerable benefits arising from machine tool verification and regular machine tool monitoring. These benefits need to be considered by industry in the process of prioritising these activities alongside production tasks, to achieve the optimal level of productivity and quality.

8.3 Machine Tool Positioning

The fundamental part of any CNC machine is the positioning of the tool. The accuracy and quality of the final product depends upon the accuracy of the machine tool. Like any mechanical device, the precision of the machine reduces with time and this affects the parts produced. It is therefore very important to ensure that the machine tool is monitored and checked at specific intervals in order to ensure machines are capable of manufacturing parts with minimum variations. Kwon et al. (2005) argued that positioning of the machine tool has a direct impact on in-process inspection using a touch probe. Instead of relying only on the touch probe measurements for part quality assurance, machine tool accuracy and capability analysis need to be taken into account. This issue is considered as a redundant process or counts as a less important issue for SMEs. The process of verifying machine tools is often seen as an additional cost and a non-productive activity that is costly and reduces profit. However, regular machine tool verification can reduce the cost of non-conforming products and increases the overall equipment effectiveness (OEE), resulting in increased profitability and greater customer satisfaction. Today, this issue is addressed by machine tool maintenance providers. A diagnostic test can be performed on the machine identifying any error in the machine tools so that deviations can be adjusted. Unfortunately, due to the lack of investment on resources and understanding the importance of the machine adjustments, this issue is seen as troubleshooting and reactive procedure rather than preventive action. Regular verification of machine tools brings confidence to companies and ensures that the equipment is performing within its accuracy specification. ISO 9001 states the following in Quality Management: Guidelines (1998):

"The supplier shall identify and plan the production, installation and servicing processes which directly affect quality and shall ensure that these processes are carried out under controlled conditions which shall include the following:

Suitable maintenance of equipment to ensure continuing capability is maintained."

8.4 The Importance of Positioning Accuracy

Helander company has invested in machine tools, tool setting probes and spindle probe verification equipment, which are not used to their full capacity. It is planned that each machine should be entered onto the "gauge register" file to ensure that a determined regular check is carried out to monitor the capability and performance of the machine tool. The outcome of this section is to reduce the maintenance costs and increase productivity by reducing downtime and producing conformance products. This study helps Helander company to develop a learning plan for the company's staff in order to understand the importance of measuring machine tool performance and to maintain the machine tool performance within agreed limits. On-going monitoring is planned to ensure the accuracy of machined components is maintained and "surprise machine tool breakdowns" are reduced to a minimum or eliminated. Furthermore, to maintain the machine tool's accuracy it is necessary to have a measured and qualified process capability control manual for each machine at the Helander company.

Based on the second law of thermodynamics, no process is ever in a perfect state of control. Therefore, the monitoring of the machine tools needs to be understood by staff of different seniority in manufacturing and production departments. In order to understand machine tool behaviour and error sources within machine tools, the benefits to each department are explained in detail, discussing why there is a need to monitor machine tool performance. Figure 8-1 shows key causes of machine errors.

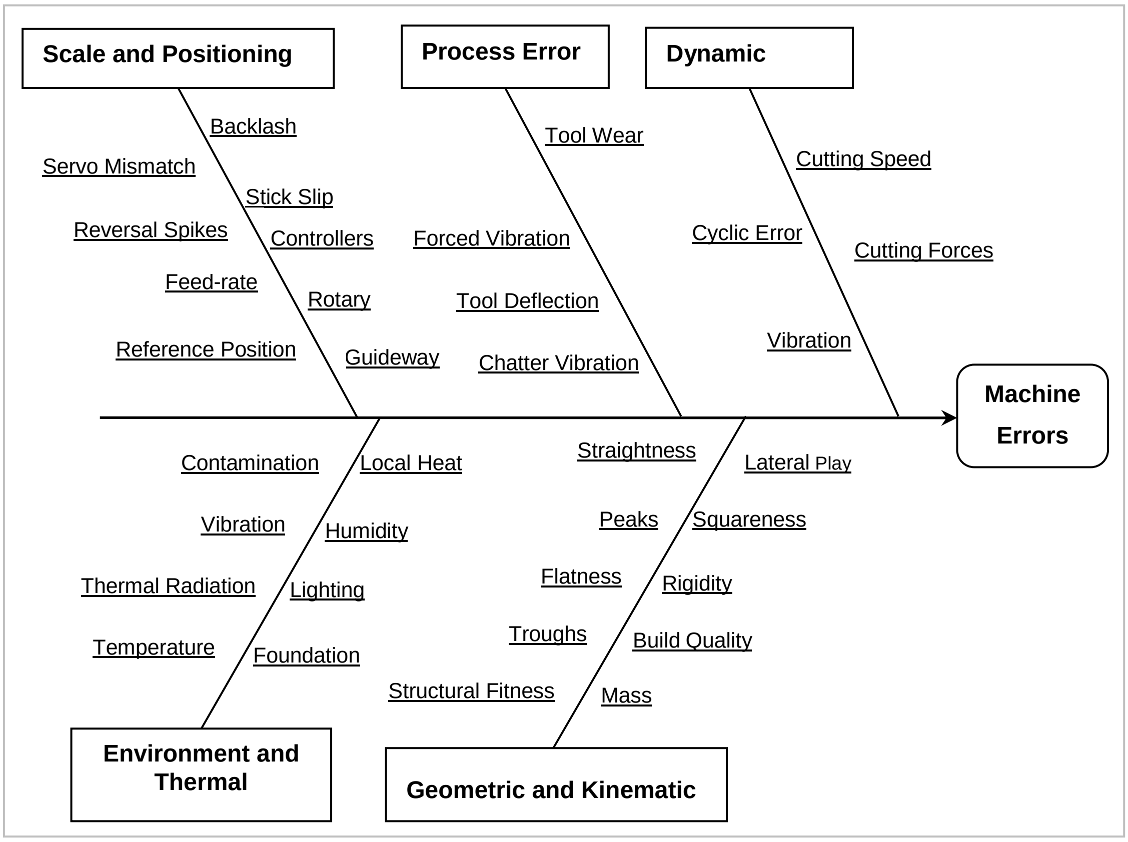

Figure 8-1 Typical factors which can affect machine performance (Adopted from: López de Lacalle, and Lamikiz, 2009)

The impact of these errors on each other and consequently on machine tool positioning along with the kinematic chain of the machine, can produce excessive positional errors in tool positioning, causing non-conformities in production (López de Lacalle, and Lamikiz, 2009). Environmental factors will affect the machine and can cause considerable errors in positioning. An example of environmental effects is thermal expansion of machine tool components due to changes in operating temperature. As a result of temperature fluctuations, different geometric positions on the machine become distorted (Muelaner et al. 2014). The accumulation of errors in different features can create inaccuracy in the scale and positioning of the tool or the machine bed. Detail explanations of each error within its own domain are explained by Renishaw (2014).

8.5 The Procedure of Positioning

In this section, the use of equipment for calibrating standard milling machines and lathes is discussed. Methods to obtain valid results for analysis and identifying the adjustments required to improve machine tool performance is clarified. Regular testing helps to predict machine failure and eliminates downtime. According to Shen et al. (2008) the volumetric positioning accuracy of CNC machine tools is the main element in machine precision. One of the common ways to test the accuracy of the volumetric positioning of CNC machine is by using a Ballbar. Use of the Ballbar helps to pick up errors caused by multiple sources, including machine alignment errors caused by distortion of the machine structure. The machine alignment error can be defined, analysed, and addressed by the Ballbar detection software and gives the company the option of a repair instead of costly parts replacement (Renishaw, 2014). The Ballbar is a major tool in CNC machine tool maintenance and servicing that helps to predict costly major repairs that can be avoided with corrective maintenance.

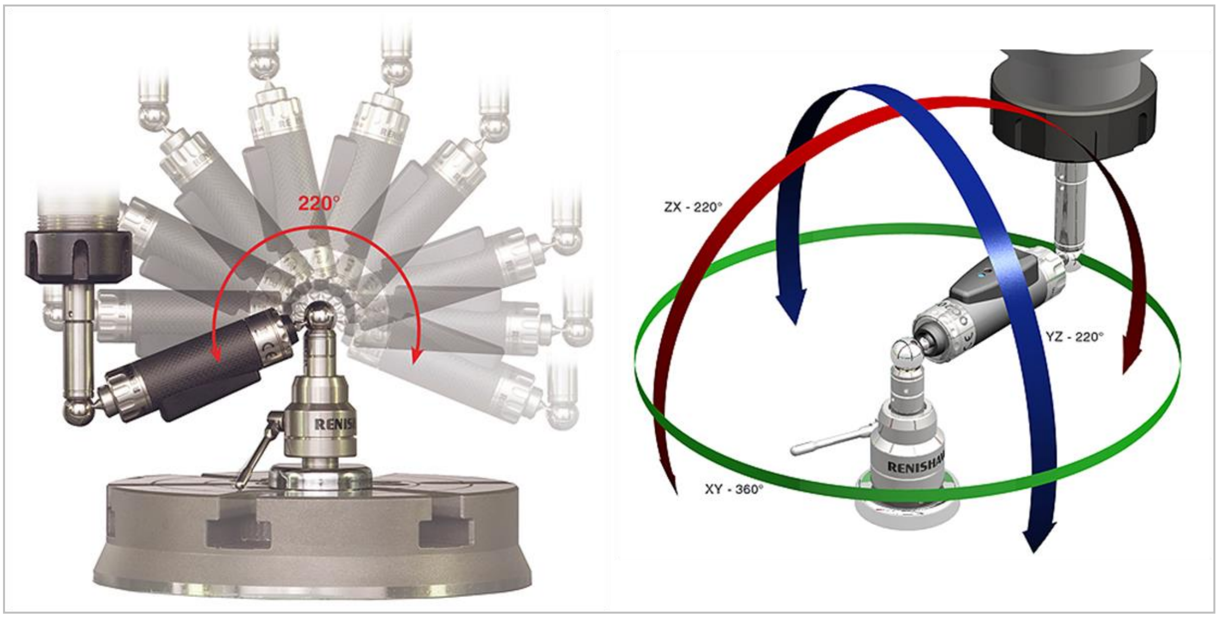

Figure 8-2 Ballbar test in 3 orthogonal planes via a single reference point (Renishaw, 2014)

When making any measurement it is impossible to measure an absolute dimension due to variations in the environment. Similarly there are variations in tolerances in machine tool itself that affect their accuracy to produce features on the components. In fact the tolerances of machine tool are much more complex as they must be accurate during movement. For instance a circular feature in a design in theory has an accurate diameter, whereas in practice the machined circle, even with the most accurate and calibrated CNC machines will have deviations and inaccuracies in the geometry of the circle. The Ballbar test measures these deviations and suggests the corrective actions to the machine in order to compensate for these errors. These deviations are the product of many factors in the machine geometry, control system and wear and tear of the machine components (Renishaw, 2014).

The process of volumetric testing starts with testing on the Z axis. Z axis testing is done by performing three checks on a Vertical Machining Centre (VMC): XY plane, YZ plane, and ZX plane (Figure 8-2). The Ballbar system can promptly diagnose and quantify machine positioning errors with the ability to produce a representative volumetric measurement of positioning accuracy (Renishaw, 2014).

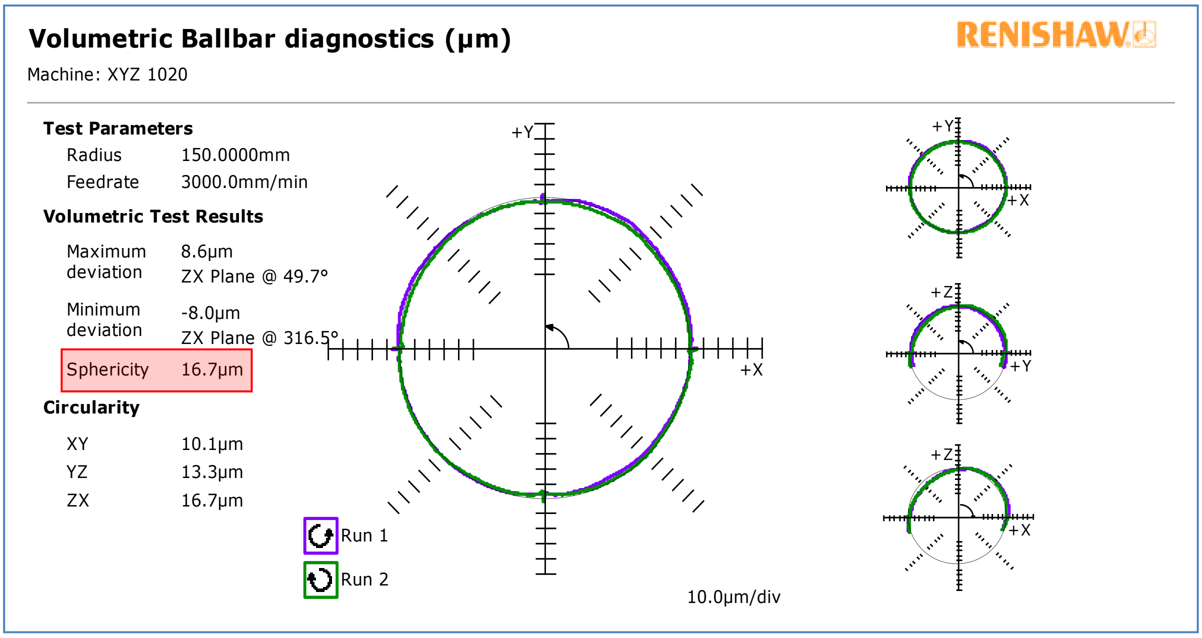

Figure 8-3 A sample of volumetric test result

After obtaining all three sets of results, it is possible to use the software to produce a full volumetric check on the machine tool. Graphical results are shown for each plane with their individual circularity results. As shown in Figure 8-3 data is displayed graphically combined with the numeric format to support diagnosing errors in each plane. The plane circularity errors which are generated during the operation of the multi-axis machine tool directly affect the machining precision. This structured process improvement tool enables Helander to improve its product verification and right first time capabilities by focussing on the appropriate use of measurement across the manufacturing operations.

According to Pahk and Kim (2001) assessing the 3D volumetric errors in such machine tools is a prerequisite for accuracy enhancement and quality assurance. These errors can be monitored over time to produce a history for comparison purposes and tolerances can be set based on captured data. This approach is perfect to verify multi-axis machine tool performance. As shown in Figure 8-3 the minimum and maximum deviation on each plane reports a sphericity error of 16.7 µm in volumetric diagnosis. Reviewing these errors can show how machine performance degrades over time, therefore corrective actions can be put into place to minimise the potential deviations. It is prudent to have a part programme for the machine tool ready and loaded into the controller, which reduces the production downtime considerably and enables a machine to be tested within 15 minutes prior to resuming production.

After all tools, methods and the importance of machine tool calibration are discussed it is important to explain the error sources and the consequences for machined components. The corrective actions should be taken to reduce and eliminate the errors and an overview of additional equipment used to improve machine tool accuracy. Renishaw Ballbar software has an effective help file that explains each error source and how to investigate and correct them. Corrections can be done reliably by testing errors on a machine with a known part (test piece) and adjusting parameters to see what effects these corrections have on improving machine tool performance (BS ISO 10791-7, 2012).

Identifying control limits for each error source within machine tools and setting control limits in the testing software is explained in detail. This is useful to determine the frequency of checks to maintain accurate machine tool performance along with predicting when a machine may fail. For instance, monitoring wear within specific parts of the machine tool and knowing when to repair the machine tool before it fails will force the company to perform reactively which is costly. Some of these machine failures are due to the weight of moving parts within the machine. The weight of the work piece can cause a repeatable displacement of the machine structure and consequently can impact and manipulate the link between the guide-ways and machine tool position and ultimately affect machine accuracy (Muelaner et al. 2014).

The next step is to modify the machine elements by setting control limits for each tool and individual tests. This will enable the test to develop to a full test procedure to comply with AS9100 and SC21[20]. The aim is to develop a balanced testing programme to ensure each machine tool is tested within specified time intervals. Finally, assistance is given in developing “in-house” test processes and procedures to cover the control of testing and due dates. The monitoring process will be utilised by the external verification body (e.g. LIMA BTC). LIMA at university of Bath is working with Helander company in interval visits to validate the testing procedure and ensure that testing programme is performing as planned by this project.

8.6 Monitoring Process of Machine Testing

At the end of the testing procedure plan, each machine tool will have its own set of control limits and individual testing programme or procedure to maintain accuracy and predict failure modes. Personnel are trained to use the testing equipment and how to interpret the test results whilst developing a matrix of machine tool controller parameters that can be adjusted to improve and maintain machine accuracy.

Success will be measured through reduced machine tool breakdowns and reduced non-conformance (scrap), which will also assist in increasing machine tool efficiency and overall OEE. Data needs to be collected prior to the start of each project so an accurate measure of success can be identified. A simple calculation sheet can be provided to identify “machine tool break down” time and the costs along with the cost of non-conformance.

The company will register the machine tools on the current gauge register (Gagetrak) and checking and verification is conducted every three months (Figure 8-4). This has been staggered so that only three machines per week are verified in order to

[20] SC21 is a change programme designed to accelerate the competitiveness of the aerospace and defence industry by raising the performance of its supply chains.

minimise downtime for production requirements. These steps should be followed by machine calibration tools, based on the data from the current study:

- Calibration frequency of machine tools is to be stated in Gagetrak
- Machine tools have allocated a unique asset number as well as their own machine tool name and machine type
- Circularity test results are printed and retained as proof of testing
- If a machine tool crashes the tests are to be repeated
- All machine tools should be treated in the same way as any other item of measuring equipment
- The periodic verification carried out on the machine tools should not negate the routine servicing or maintenance carried out by the service providers
- A list of all machine tools with imminent certification expiration should be given to the team leaders at the beginning of the each month

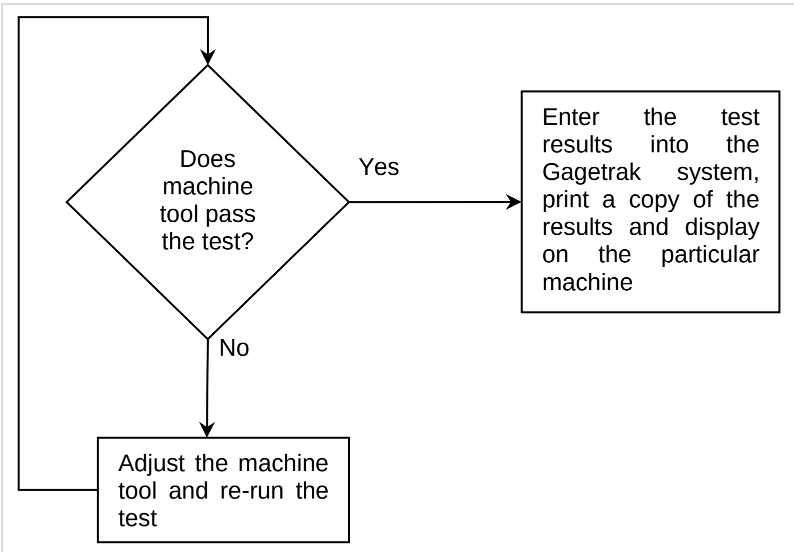

Figure 8-4 Proposed process of periodic verification on machine tools at Helander

The quality department is responsible for ensuring that the production department is informed of which machines require verification at the beginning of each week. Subsequently, the production department is responsible for verifying the machines and producing evidence for the quality department on weekly routine. This process is sound and auditable with individual control limits for each machine and the process has been added to the Helander ISO 9001 manual.

The importance and methodologies for machine tool verification and condition monitoring have been presented. At Helander, machine tool repeatability is verified by using a series of target points (Figure 8-5) that were measured by laser interferometers and collimators. By comparing this information, it is possible to find errors in straightness, parallelism and concentricity (de Lacall and Lamikiz, 2009).

Figure 8-5 Measuring the rotary positioning accuracy of an axis (Renishaw, 2014)

The challenge is that the accuracy and repeatability values can differ significantly depending on the measurement procedures. For instance, the accuracy is different when fewer control points are measured. This difference in results makes it very difficult to compare the performance of different machine brands (Quality Management, 1998). The use of Ballbar diagnostic not only shows conclusive proof that servicing or re-calibration work is needed, but also enables the verification process to be carried out quicker in comparison to conventional methods.

The benefit of using the Ballbar system for verification includes automatic machine tool errors diagnosis, identification of the causes and remedies and determination of the machine tool capability. Identification of the machine tool capability is a vital aspect of design for verification, as it allows design rules to be formulated, making a link to the engineering specifications. Examples can be tolerances and surface roughness that can lead to superior and cost effective verification of products that can improve the process capability. This is vital to SMEs, as the verified machine tool will return to the production loop in a short period of time, depending on corrective actions.

The benefits of this chapter to Helander and any SMEs are unlimited as adjustments in machine tools could substantially reduce the risk of failures in manufacturing. Regardless of the amount of time that the machine programmers and the engineering team spent on the procedures if the machine does not work to its accuracy the final product would still be poor in quality.

In this chapter the author emphasised the importance of performing adjustments to the machine tool and benefits of machine checking and their link to time saving, cost and productivity are described in the format of bullet points. Also the probable impact of machine tool accuracy on decision making process within the planning department is explained.

The methodology for in-process control and verification of machine tool positioning for the SMEs recognized and conducted by investments made at Helander as a case study. At the end, the process of control and monitoring the Ballbar testing process is described in detail and records kept in record logs for quality management system.

Chapter Nine: Finishing of Additive Layer Manufactured Parts

9.1 Introduction

Additive layer manufacturing (ALM) is a modern fabrication process that allows near net shape manufacture of engineering materials. This method has been primarily used in the past for plastic, polymer and nylon materials. This chapter outlines the use of ALM for manufacturing artefacts from hard metal alloys. These alloys include nickel-based superalloys, such as Inconel 718. ALM parts are being used to manufacture gas turbines components with high creep and corrosion resistance. Conventional methods for producing net shape components from these hard alloys involve machining, which is a costly and slow process compared to ALM (Thomas and Gilbert 2014). The drawback, however, is the potential degradation of the alloy's microstructure. As part of this MPhil project, a comparison was made of the properties of Inconel 718 machined conventionally at the University of Bath and parts produced by ALM within the Helander supply chain (Banks, 2015).

9.2 An alternative to machining - Additive Layer Manufacturing

Additive Layer Manufacturing is a method of adding material in the form of layers made by fusing fine powders in order to make physically tangible parts. Each layer normally has equal thickness and they are deposited on a platform and then on top of each other to generate a 3D dimensional component (Figure 9-1). As a result of the constant layer thickness, the created component will have a stair-stepping shape on the surface (Gebhardt, 2011). The method was initially employed to manufacture parts with resin and then nylon and since the beginning of 90s metal components have been created.

Figure 9-1 Principle of additive layer manufacturing (Gebhardt, 2011)

This technique has advantages and disadvantages over other manufacturing techniques such as subtractive manufacturing and forming manufacturing. The main disadvantage is the time involved the cost and inaccuracy in size of engineering parts, poor quality of the manufactured component and the limited range of materials which can be used to produce the desired part. The main advantage over other methods is freedom of design with almost no limitations in creating the conceptual idea.

Gu (2015) defined the process of generating ALM parts based on the following steps.

- Create CAD model of the component
- Make the solid format of the part with computer aided design (CAD) software
- Convert the CAD model to STL format
- Convert the part to match the ALM CAD file format designed for ALM application known as stereolithography (STL).
- Slice the STL file into thin horizontal layers
- Edit the file in STL format allowing the user to adjust the size, location and orientation of the file.
- Create the part in the thin layer by layer mode
- Run the ALM machine to construct the part in the layer by layer format as defined in the last step.

- Post process the manufactured part
- In general use Hot Isostatic Pressing (HIP[21]) to achieve the desired densification level and mechanical properties.

There are a few methods of manufacturing metals via ALM method that are described in Table 9-1. Each method is suitable for a range of materials. For instance Direct Metal Laser Sintering (DLMS) can be used for Inconel 718, Cobalt Chrome and a range of Stainless Steel alloys while it cannot be used for Stellite 6 due to the existence of tungsten[22] in its composition and the need to melt this element as a powder.

Table 9-1 Comparison of some common ALM methods for metals (Adapted from Gu, 2015)

Process	Description	Layer thickness (μm)	Dimensional accuracy (mm)	Surface roughness R_a (micrometres)
Direct metal Laser sintering (DMLS)	Laser sintering	20 – 100	High, ± 0.5	14 - 16
(Selective laser melting) SLM	Laser melting	20 – 100	High, ± 0.4	9 - 10
Direct metal deposition (DMD)	Laser cladding	254	NA	~ 40

DMLS technology is capable of creating highly complex shaped functional metallic components that simply cannot be produced with any other manufacturing method. Additive layer manufacturing (ALM) is still considers as a young technology. There has been almost no effort made to standardize DLMS. The American Society of Mechanical Engineers (ASME) in cooperation with the American Society for Testing and Materials (ASTM) has started the development of standardization procedures that are still ongoing that can be found on Gebhardt (2011).

[21] Hot isostatic pressing (HIP) is a manufacturing process used to reduce the porosity and increase the density of certain metals. It helps to improve the material's mechanical properties and workability.
[22] Tungsten or Wolfram, is a chemical element with symbol W and atomic number 74

9.3 Replacing subtractive manufacturing with combined Additive and Subtractive manufacturing

There are five main methods of manufacturing: joining, division, transformative, subtractive, and additive manufacturing (Nassehi et al, 2011). The latter method is a hot topic in today's industry, as it has the potential to revolutionize techniques for replacing wasteful large-scale manufacturing technologies with simple and resource-efficient solution. As technology goes forward, demand for more complex products is increasing (Brown 2012). Figure 9-2 shows an example of a complex part that is either costly to make with current methods or cannot be produced via other manufacturing methods. ALM seems to be the answer to these demands, as it opens up a new way of designing materials and issues with DFM are not a challenge for designers. There is the potential for making huge savings in manufacturing parts as machined parts need not be sent to sub-contractors for different operations. Time is saved and there are reductions in the risk of failure in producing parts (Royal Academy of Engineering, 2012). ALM can eliminate or significantly reduce the storage and inventory within companies and increase the cash flow in organisations.

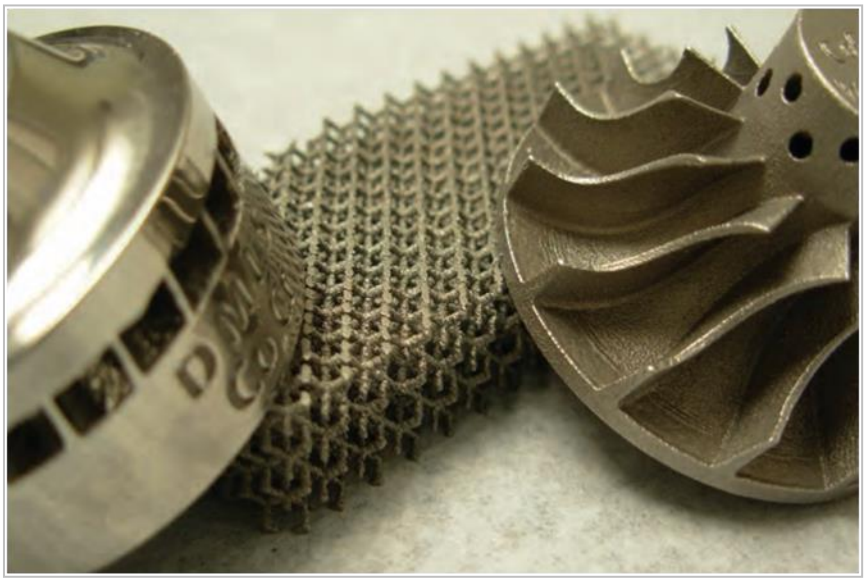

Figure 9-2 ALM parts similar to Helander manufactured components that is costly or may not be able to be made with subtractive method (Royal Academy of Engineering, 2012)

The management at Helander has proposed that the method of manufacturing should change from subtractive to additive to remain competitive in the market. A product that has been manufactured for over 10 years at Helander was chosen as a case study. Nowadays, the material for this component is stainless steel 17-4PH. The component is made in two sections and then an electron beam weld process is used to weld the components to each other (due to lack of accessibility by 5-axis machine) by a subcontractor operation. The component is made in 15 different operations in batches of 30 pieces and the lead time for a batch size of 30 is over 3 months[23].

The history of the parts being manufactured at Helander over a period of 10 years is 2240 pieces up to 2014 according to the MRP system. Initially, this particular component was made from Stellite 6 alloy via a casting method and then machined to finish the critical features. The strong characteristics of Stellite 6 make the part long lasting in its operations (to be used in highly corrosive and abrasive environments). Problems due to inconsistency in casting products such as porosity and breaking of the part in operation due to the weak structure of castings, forced Helander to use other methods. The replacement method is to cut the piece in half, machining the stainless steel 17-4PH material component and perform a vacuum brazing operation to join the component. Figure 9-3 shows a section of the manufactured part by the ALM method (right image) and 5-axis machine (left image).

Figure 9-3 Additive vs. machined part[24]

9.4 Case Study on Finishing of Additive Manufactured Parts

At Helander, the manufacture of components conventionally machined with a 5-axis machine for the oil and gas industry is compared with manufacture with the ALM method. The business case was made and described to a major customer. Cobalt chrome alloy was proposed for use as it has better characteristics in abrasive and corrosive conditions in comparison to stainless steel 17-PH. The customer agreed to make test pieces by the ALM method for their laboratory analysis. Based on business

[23] This is due to capacity issues at Helander and machining operations and sub-contract operations to finish the batch size.
[24] The full part cannot be shown due to company policy

plan proposed to Helander customer, if the project goes forward, Helander can invest in ALM machines and have one ALM machine in-house. The financial results show an ROI time of 8 months subject to approval from customer however it does require more detail review.

A comparison between the cobalt chrome alloy (ALM material) and the conventionally used Stellite 6 alloy is shown in Table 9-2. The results are similar in many elements with some minor difference on the percentage of certain elements. The only major difference is that the Tungsten is not included in cobalt chrome due to its high melting temperature (3422°C). The high temperature of tungsten is not within the capability of ALM machines therefore it is not included due to the adverse effect it will have on the solidification of the alloy.

Table 9-3 demonstrates that there is little difference in the mechanical properties of the two alloys. At the beginning of the process, the cost of manufacturing per piece by ALM method is higher due to the lower batch sizes. However, if the full platform in the ALM machine is in use, the cost per component is slightly less than the machining equivalent. The difference would be a much more durable material and much faster delivery (up to one week) for a batch of 30 pieces.

Table 9-2 Chemical composition of Cobalt Chrome alloy vs. Stellite® 6 (Adapted from CES EduPack, 2015; Renishaw, 2015 and EOS 2015)

	Co-28Cr-6Mo	Stellite 6
Co	60-65 %	Base
Cr	26-30 %	27-32
W	-	4-6
C	≤ 0.16 %	0.9-1.4
Ni	≤ 1.0 %	< 2
Fe	≤ 0.75 %	< 2
Si	≤ 1.0 %	< 2
Mn	≤ 1.0 %	< 2
Mo	5-7 %	< 2

Table 9-3 Mechanical properties of Cobalt Chrome alloy vs. Stellite® 6 (Adapted from CES EduPack, 2015; Renishaw, 2015[25] and EOS, 2015[26])

	Co-28Cr-6Mo	Stellite 6
Hardness	35 – 45 HRC	37 – 45 HRC
Density	8.3 g/cm³	8.45 g/cm³
Tensile Strength	1100 ± 100 MPa	Cast 790 – 840 MPa Wrought 1100-1300 MPa
Yield Strength	600 ± 50 MPa	700 MPa
Coefficient of Thermal Ex	13.6×10^{-6} m/m°C	$10\text{-}15 \times 10^{-6}$ m/m°C
Mass Loss in Sea Water	-	≤ 0.05mm per year at 22°C
Fatigue Life	560 MPa in 10^{7} cycles	435 – 675 MPa in 10^{7} cycles
Thermal Conductivity	13 - 18 W/m°C	13 - 17 W/m°C
Max Operating Temp	approx 1150°C	837 - 1050°C
Melting Point	1350 - 1430°C	1260 - 1320°C

The comparison between different alloys shows the possibility of using ALM for hard to machine alloys such as Inconel 718 and cobalt chrome alloy. The investigations show the financial and time benefits of using ALM over subtractive manufacturing for certain parts manufactured at Helander (the results cannot be presented due to Helander's data protection policy). The issue could be a drawback for Helander, as the company will reduce their order volume per year for those parts, but a concern is that due to the competitive nature of the market, the opportunity to manufacture these components might be taken away from Helander by competitors using ALM machines.

Other learning points that explained for the benefit of Helander are listed below:

- ALM seems mature enough to be used in production for non-sensitive industries (i.e. oil & gas)
- Benefits of ALM are potentially higher compared to other conventional manufacturing methods
- ALM has its own limitations (material, limitations in size, initial cost, and lack of standard methods for manufacture)
- Standard manufacturing methods such as forming and subtractive manufacturing are likely to be replaced by ALM

[25] http://www.renishaw.com/en/renishaw-enhancing-efficiency-in-manufacturing-and-healthcare--1030
[26] http://www.eos.info/en

Chapter Ten: Discussion

Due to having different topics in each chapter of the thesis it is decided to break the discussion for each chapter separately. This chapter explains the discussions related to each chapter within the scope of the project.

10.1 Material Evaluation of Helander Alloys

Inconel 718 is one of the common materials used at the Helander company. The nickel based material is hard to machine due to its high strength and hardness. It is explained in section 5.2 that Inconel 718 suffers from minor variations in machinability which relates to variations in microstructure and heat treatment as a raw material. These minor variations bring uncertainty in machining, which can increase tool wear or lead to underutilisation of the machining operation. The results of material analysis from different suppliers show how these small variations make an impact on machine force. In section 5.2 results of material analysis shown the variations in Inconel 718 from different batches the differences in their grain structure and the impact machining on each batch are also varies. To address this issue and reduce material variation, a study was proposed as further work to analyse changes in heat treatment temperature and cooling method as well as narrowing down the chemical composition to a lower limit. In section 5.3 the results of hardness test is evidence of the need to alter the machine elements (feeds and speeds) during machining operation. This strategy will potentially increase the cost of raw material, but will extend the life of the tooling and reduce the scrap rate for high value components.

10.2 Methods of Process control & Process Verification

In order to manufacture products right first time and every time, the correct process needs to be in place. To manufacture repeatable products, a close look at the causes of variation and making changes in the raw materials or the production process is essential which is explained in more details in sections 6.1 and 6.2. This issue can be resolved by using process control and verification tools. Helander, as process owner, will define product characteristics to minimise the combined production, labour and machine cost and the cost of quality losses such as scrap, rework and repair.

In section 6.3 the use of statistical tools such as gauge R&R (section 6.3), SPC (statistical process control) and machine capability was explained and it was shown that these processes will increase the company's confidence to establish and maintain a robust process. Many customers are demanding evidence from FAIR (first article inspection report), PPAP (production part approval plan), APQP (advanced product quality plan) as part of the NPI (new product introduction) process. PPAP is a standard process that helps to ensure the processes used to manufacture parts is consistent and can reproduce the parts at stated production rates during routine production runs. APQP is a quality framework intended to produce a product quality record to be used for developing new products based on customer requirements in an organisation (Rolls Royce supplier training, 2013). Section 6.2 shows the map of the PPAP process that is implemented at Helander. The sample slide used as a guideline on how to use the IPI software for PPAP process is shown in Appendix 5. FAI (first article inspection) is required for each process as evidence for the method of manufacturing. When any change happens in the process of manufacturing, such as modifications in the use of different inserts, changes in machining processes and the use of a new supplier for the particular sub-process, the new FAI should be filled and kept in quality documents.

These elements are missing in Helander's manufacturing engineering sector. Section 6.5 and 6.6 presents a detailed analysis of two manufacturing parts (simple and complex) that are used as a case study to identify the savings that could be made if the detailed work instruction and control plans were in place. The SWOT analysis shows the cost of quality in each case. Also benefits and financial savings achieved by implementing the above concepts are evaluated. The pre-requisite of such methods is to have a review plan for each new part and for every repeat part in production and to adjust their process with CAPA (corrective and preventive actions) processes.

10.3 Control of Helander's Manufacturing Process

After implementation of NPI and all pre-requisites at Helander, improving the uniformity of the process was necessary. The process was approved by the customer and passed the FAIR stage, but because everything was done on a piece of software (IPI Solutions) and on a paper document, required elements were not in place. The required elements can be physical, such as tooling or special gauge, or they can be documents, such as process flow and sequence of information flow within the organisation. Therefore, various cross-functional diagrams and organisation maps need to be designed (Sections 7.3 and 7.4) and held in the quality system to explain what should be done at each stage of manufacturing. Additionally, SOP (standard operating procedure) is required to show the process for each and every operation (including deburr, wash, and pack) and standard forms for tooling, set ups, visual work instructions, stage drawings, and other forms to enrich the operator knowledge to execute best practice operations.Maintenance of operation documents in the manufacturing engineering department and process flows in quality system should be the ultimate goal of the organisation in order to have control over the manufacturing process.

10.4 Performance Measurement of Helander Machine Tools

Machine tool accuracy is the most critical issue in precision engineering. Section 8.1 describes that regular machine tool positioning will increase confidence and decrease the number of non-conforming products. Repeatability of the machining operation depends on consistent performance of the machine tool and its ability to accurately position the tool tip. The tool tip positioning should be verified and monitored frequently to ensure the accuracy of the machined artefact. This issue can be resolved with in-house Ballbar testing. Management should be aware of the importance and benefits of the machine tool and regular checks required for the test. At Helander company, this issue has to date been under-prioritised due to lack of information about the importance of the Ballbar test. Benefits of regular machine accuracy are listed in section 8.2. The machine tool study was reviewed and trained to senior engineers. Errors that will lead to machine error were categorised and the compensation techniques addressed based on the Renishaw Ballbar test software (Section 8.4). In section 8.6 monitoring plans are set out to check the machines regularly. In order to maintain machine accuracy, the production of a measured and qualified process capability control manual for each machine is recommended.

10.5 Finishing of Additive Layer Manufactured Parts

Additive manufacturing is a new method to be used in manufacturing. Many organisations believe additive manufacturing is not currently mature enough to be used in production and that it is merely good for proof of concept and prototype modelling in the design sector. In section 9.2 it is discussed that ALM can be used as an alternative to many machining operations and only the finish machining stage can be perform as the final stage. This will lead to substantial savings in cost and increase in lead time to market for certain parts in production. In section 9.3 the process of ALM is explained by making a business case and bringing evidence of proof of durability for additive manufactured component. Helander is going to invest more in this area. The use of additive manufactured parts for the oil and gas industry is more probable due to reduced standards for materials in comparison to other business sectors, such as the aerospace, automotive and nuclear industries. Sample parts were made by ALM sub-contractors (Section 9.3) and finish machining operations were performed at Helander before the final part was sent to the customer in the oil and gas sector. The next step was to use the sample part in an oilrig drive shaft assembly for testing and validation. Preliminary responses from the test were positive (based on management feedback - company policy prevents the test results from being published) and more test pieces were ordered for examination in different environments. Future works in this area will investigate which manufactured parts are more suitable to be made using the ALM method.

10.6 Addressing customer needs for introduction of new products

A review of the literature (Chapters 3 and 4) failed to reveal an acceptable solution to new product introduction process at small to midsize organisations. A new product introduction procedure (Chapter 6) was investigated by the author, and the elements required to achieve a robust system for new products was prepared and implemented at the case study company. The objective for repeat products was also to rewrite the operation stages in unified format based on company’s capability. The new standard operating procedure was designed along with process mapping at the company to address the issues with non-conformances from major customers.

The procedure gave the company an advantage over their competitors, and allowed them to win new long-term contracts in well-recognised nuclear and defence industries. Having these procedures in place shows that the company has the capability to follow customer flow-down requirements and comply with customer needs.

Chapter Eleven: Conclusions and Future Works

11.1 Conclusions

Superalloys have been developed for use in harsh conditions. For the same reasons, they are hard to cut and machine to the specific required dimensions. Studies performed in this area focus on the chemical properties and change in physical properties of material before and after machining. It has been shown that machining has a big impact on the hardness of the alloy, especially at the surface, which leads to uncertainty in the use of machine parameters as well as measurement instability in the final manufactured component.

The results from the machining of different parts at Helander show that significant savings can be made in different areas to speed up the manufacturing lead time and increase the customer satisfaction by reducing the non-conformance parts. These easy steps seem rational in a manufacturing environment, but they do not exist within SMEs since engineers are tied-up with fire-fighting day-to-day (and repeat) problems.

As discussed, most uncertainties in production could be reduced by applying control plans in the supply chain and in the manufacturing process itself. The idea of having “sealed” manufacturing[27] is logical for repeat products, however best practices need to be examined for the parts. There are many operations in the company that are done by using engineers’ experience rather than clear work instructions. The use of standard operating procedures is highly recommended in these cases, with different forms and procedures designed, mapped and implemented throughout the company. These elements are essential in identifying best practice and eventually turn them into sealed production procedures.

[27] Sealed manufacturing: Expression used commonly in manufacturing industries referring to (repeatable) best practice manufacturing method

In the manufacture of new products, the NPI procedure is defined and the company process is mapped to demonstrate what production steps are required. The design stage of the manufacturing method should be followed in a structured manner to ensure no element is missing in the production phase. With complex parts, it is essential to have a project coordinator responsible for preparing the different required elements. These elements are listed, explained, and implemented within the company to address the needs for new product development.

Finally, the machine tool verification technique is explained and the importance and benefits of having regular machine checks listed. The machine tool accuracy and machine health check can be the root cause of many variations in manufactured parts. As an alternative approach to 5-axis machining, the ALM process has been introduced and the benefits of using this process explained to a potential customer by manufacturing a sample part. The testing stage was positively received by the customer and the development stage continues to be assessed through further work on this project.

11.2 Future Work

Research into different methods for manufacturing superalloys such as the use of different machining methods, different inserts, and use of different machining elements (i.e. feeds and speeds) has been ongoing since their introduction. Process control and supply chain control at the SME level will reduce the risk of variability often experienced when machining superalloys. In order to reduce the tool wear and control the alloy's machinability, research to identify the optimum chemical composition and heat treatment of the alloy combined with the ideal cooling method can be considered as future work.

Other research gaps in the manufacturing industries are the lack of reviewing and understanding customer needs in the NPI process. Customer requirement procedure and its sub documents referenced to the customer purchase order are the main documents required to be reviewed by suppliers. In many instances, the customer quality standards (or customer flow-down requirements) are ignored or categorised as less important than manufacturing the components themselves. Many SMEs, including Helander, found that suppliers start manufacturing the component before fully understanding the customer requirement. As the manufacturing starts, corrective actions become more challenging. There are processes in place to answer arising challenges (Shrotri et al. 2014). These processes include NPI, PPAP, APQP and control plan, PFMEA, FAIR and VSM. Each of these methods requires understanding and implementation within the organisations in line with their configuration. Little has been done to answer these needs at the SME level. Understanding these relatively simple processes is a big challenge for SMEs and having proof of these concepts and procedures is a big advantage for gaining approval from major industries (i.e. Rolls Royce). The main companies in the automotive, aerospace and nuclear industries are asking for more standardised processes in order to evolve leaner and more traceable supply chains. Adopting these processes will be a major advantage for SMEs if they wish to have long-term business with major industries.

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Appendices

Appendix 1

PPAP elements (Based on Rolls Royce PPAP guideline)

PPAP Elements

Rolls-Royce

	PPAP Element	
1	Product Definition / Engineering Specification	*Build in Quality through* **Product Quality Planning**
2	Authorised Engineering Change documents	
3	Customer Engineering Approvals	
4	Design Failure Mode and Effects Analysis (Design FMEA)	
5	Process Flow Diagram	
6	Process Failure Mode and Effects Analysis (Process FMEA)	
7	Control Plan	
8	Test / Inspection Criteria and Planning	
9	Qualified Laboratory Documentation	
10	Packaging and Labelling Standards and Documentation	
11	Sample Production Product	*Understanding manufacturing potential through* **Production & Rate Proving**
12	Measurement System Analysis Studies	
13	Dimensional Results	
14	Records of Material / Performance Test Results	
15	Initial Process Studies	
16	Process Control Surveillance Results	
17	Initial Manufacturing Performance Studies	
18	Customer Specific Requirements	**Customer-specifics**
19	First Article Inspection Report (FAIR)	**Production Product Approval**
20	Process Control Document (PCD)	
21	Production Submission Warrant (PSW)	

Appendix 2

The PSW (the final element of PPAP) form designed for Helander use is shown below. It should be filled by the PPAP coordinator at the end of the process.

HELANDER	Production Submission Warrant [PSW]	PSW No.

PRODUCT INFORMATION **Page No. 1 of 2**

Product Name: ____________ Product Number: ____________

Reference / Vendor Code: ____________ Drawing Number: ____________

Agreement Reference: ____________ Engineering Change / Issue Level: ____________

PRODUCTION SUPPLY ORGANISATION (PSO)	INTERNAL CUSTOMER ORGANISATION
Organisation Name	Customer Name / Division
Street Address	Customer Authorised Representative (Name)
City ____________ Region ____________	
Postal Code ____________ Country ____________	Application (Project / Programme)

REASON FOR SUBMISSION

☐ Initial submission	☐ Subcontractor/Sub-tier or Material Source Change
☐ Engineering Change(s)	☐ Change in Product Processing (manufacture, assembly)
☐ Tooling: Transfer, Replacement, Refurbishment, or additional	☐ Products produced at additional or alternative Location
☐ Correction of Discrepancy	☐ Other - please specify below
☐ Customer requested production verification	

Comments

APPROVAL SUBMISSION LEVEL (Also use section 1 of sheet 2)

○ **Level 1** ○ **Level 2** ◉ **Level 3** ○ **Level 4** ○ **Level 5**

DECLARATION (Also use section 2 of sheet 2, and when appliable section 3)

I submit this Production Submission Warrant (PSW) and accompanying data to provide objective evidence of compliance to all Production Product Approval Process (PPAP) requirements and as confirmation of the product / process capability and capacity to support ongoing supply. I also certify that documented evidence is on file and available for review.
I have noted any deviations from this declaration using sheet 2.

PSO Authorisation: (Print Name/Sign)	Title	Date	Phone Number

FOR CUSTOMER USE ONLY

☐ **Approved** ☐ **Interim Approval** ☐ **Rejected**

Interim Approval Status ☐ **B** ☐ **C** ☐ **D** ☐ **E**

Agreed period or quantity for shipment: ☐ Specific actions required *(see comments box)*

☐ Concession required for shipment Concession No. ____________

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Accept	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Reject	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Not Required	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Comments

Customer Authorised Representative (Print Name/Sign)	Title	Date	Phone Number

HELANDER	Production Submission Warrant [PSW]	PSW No.

SECTION 1: SUBMISSION CONTENT **Page No. 2 of 2**

Note: For boxes ticked "No" and where the element is applicable use section 3.

Yes	No	ELEMENT DESCRIPTION *(tick)*	Yes	No	ELEMENT DESCRIPTION *(tick)*
☐	☐	1 Product definition / engineering specification	☐	☐	11 Sample Production Product
☐	☐	2 Authorised Engineering Change documents	☐	☐	12 Measurement System Analysis verification
☐	☐	3 Customer Engineering Approvals	☐	☐	13 Dimensional Results
☐	☐	4 Design FMEA	☐	☐	14 Records of Material / Performance Test Results
☐	☐	5 Process Flow Diagram	☐	☐	15 Initial Process studies
☐	☐	6 Process FMEA	☐	☐	16 Process Control Surveillance Results
☐	☐	7 Control Plan	☐	☐	17 Initial Manufacturing Performance studies
☐	☐	8 Test / Inspection Criteria and Planning	☐	☐	18 Customer Specific Requirements
☐	☐	9 Qualified Laboratory Documentation	☐	☐	19 First Article Inspection Report (FAIR)
☐	☐	10 Packaging and Labelling Standards	☐	☐	20 Process Control Document (PCD)

☐ Other - please specify below

SECTION 2: DECLARATIONS CONTINUED

Note: For boxes ticked "No" and where the element is applicable use section 3.

Yes	No	
☐	☐	All Customer / Design Engineering requirements are properly understood and recorded.
☐	☐	The requirements of the Production Process Run have been satisfied and associated data evaluated.
☐	☐	All the results demonstrate conformance to Customer / Design Engineering requirements.
☐	☐	Satisfactory Process Control Surveillance has been carried out and conformity to requirements is deployed within the production manufacturing process.
☐	☐	Initial Manufacturing Studies demonstrate rate potential to customer demand rate requirements .

Please state Customer demand rate ____ Unit ____

☐ If there are any deviations from the declarations made (sheet 1 and 2) tick and state specifics below

Comments

SECTION 3: FOR INTERIM SUBMISSIONS ONLY

Yes	No		
☐	☐	Interim Corrective Action Plan included	Commitment date of re-submission: (state date)

Comments

Appendix 3

The practice of gauge R & R performed on a set of measurement tools shows the capability of each tool for different ranges and tolerances. A sample of the tools that were analysed is shown in the following table.[28]

Digital Micrometre

Component size (mm)	Specification Tolerances (mm)								
	± 0.005	± 0.010	± 0.025	± 0.050	± 0.100	± 0.250	± 0.500	± 0.750	± 1.000
<1									
5									
10									
25									
50									
75									
100									
150									
200									
300									
400									
500									
1000									
>1000									

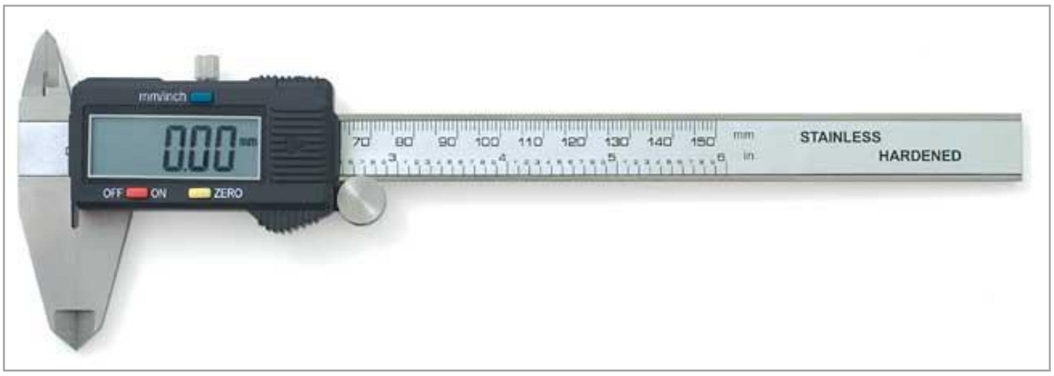
[28] This practice performed based on Rolls Royce, Measurement System Analysis, How-to Guide, Version 6.1, August 2013 and Guide to Dimensional Measurement Equipment, Version 3.1, May 2013

Analogue Micrometre

Component size (mm)	Specification Tolerances (mm)								
	± 0.005	± 0.010	± 0.025	± 0.050	± 0.100	± 0.250	± 0.500	± 0.750	± 1.000
<1									
5									
10									
25									
50									
75									
100									
150									
200									
300									
400									
500									
1000									
>1000									

Digital Calliper

Component size (mm)	Specification Tolerances (mm)								
	± 0.005	± 0.010	± 0.025	± 0.050	± 0.100	± 0.250	± 0.500	± 0.750	± 1.000
<1									
5									
10									
25									
50									
75									
100									
150									
200									
300									
400									
500									
1000									
>1000									



Appendix 4

Within the KTP programme, a set of forms has been designed at Helander to be used along with their current manufacturing route cards. These forms are by no means replacements for any document in the manufacturing work pack but they clarify the procedure. Due to Helander data protection information in these figures is limited or blacked out.

HELANDER

WI No: 0002 **Part Number:** [redacted]

Work instructions for [redacted] **hole OP 20**

Fixture No: NCF 0001 use with loading block NCF 0002

Pictures cannot be shown due to company policy

Load fixture on machine with front forward position and clock OD around B axis and adjust within 0.050 TIR (Total Indicator Reading)

Pictures cannot be shown due to company policy

Clock ARL loading face adjust within zero-zero at each end. Set axis to zero in G10 datum
Datum line at start of program (these set the G54)
Air blow fixture (to clean all swarf, etc)
Load billets into fixture using setting block NCF 0002 plus tighten central bolts in the following order with even pressure

1 3 2 4

After tightening ensure that 0.1mm shim will not insert between billet and fixture

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Work instruction explains the procedure of loading the part on the machine

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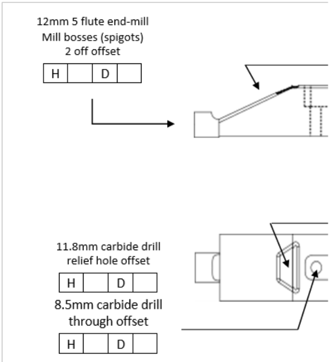
WI Drawing No: 0002 **Part Number:** [redacted]

Work Instruction drawing for [redacted] **OP 20**

Work instruction No.	Part No. & Issue	Operation No	Part Description	Date issued
0002	[redacted] / B	20	[redacted]	

Note: Use stage drawing [redacted] & WI 0020 for setting and loading



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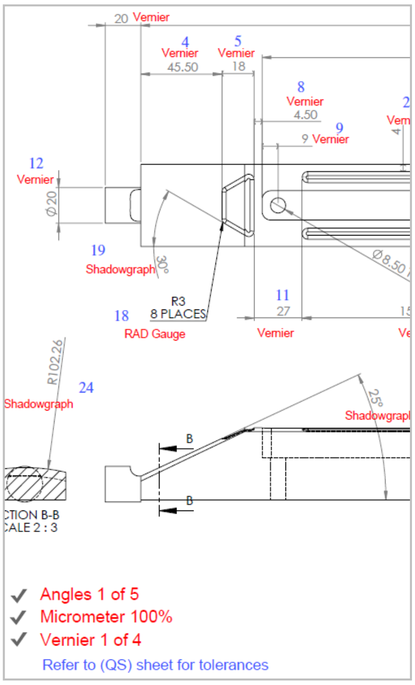
Work instruction drawing shows the offsets and relevance of each tool to each feature



Stage drawing to be used as a guideline for frequency of measurement and use of the right gauge for the right feature

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Quality Schedule No: 0002 **Part Number:** [redacted]

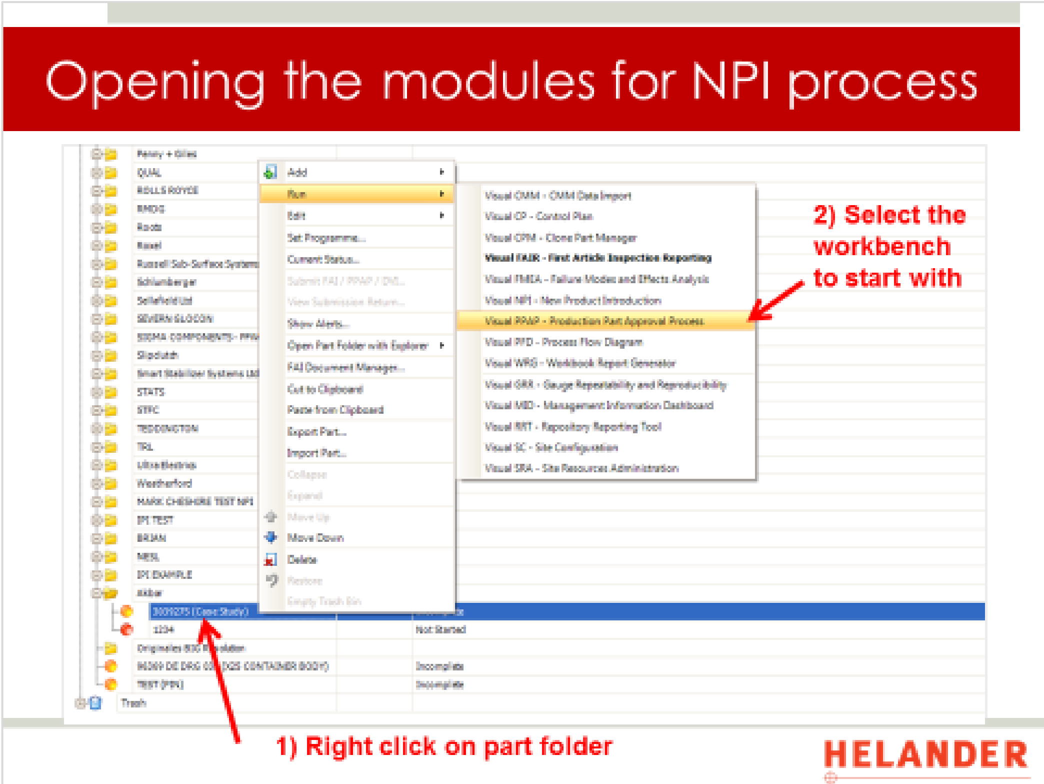
Quality Schedule for [redacted] **OP 20**

	Quality Schedule No.	Part No. and issue	Part Description																		Date issued		
	0002	[redacted] / B	[redacted]																				
	Feature and tolerance mm	Inspection Equipment	Check Frequency	First Off	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Size Measured	Last Off
1	360 (±0. 2) length	Height Gauge	1 – 4																				
2	230 (±0.2) length	Vernier	1 – 4																				
3	150.2 (±0.2)	Vernier	1 – 4																				
4	45.5 (±0.2)	Vernier	1 – 4																				
5	18 (±0.2) both sides	Vernier	1 – 4																				

Quality Schedule form to record the measured size of different features

Appendix 5

The sample slide used as a training guideline on how to access different sections of the IPI software for PPAP process.



Appendix 6

The list of Helander machinery with their working volume and cooling methods

Fully Managed Supply Service - Assembly Capability - CMM Inspection
We can provide a full service to include: project mgmt, supply of materials, all manufacturing steps including treatments, processes, inspection/testing and third party validations.
We can provide fully manufactured, assembled and tested items.
We have 4 Co-Ordinate Measuring Machines (CMM's) - all have Renishaw probing systems. These are operated within temperature controlled environments

CNC TURN/MILL CENTRES (multi-axis)

M/C Make - / Model	Max workpiece (chucking / shaft work / barwork)	Total Axes	Y Axis	Tool Stns	Other Features
MAZAK - INTEGREX E650H	Chucking: to Ø500mm. Shaft work: Ø360mm x 3000mm between ctrs	5	YES	80	Work steady - HP Coolant
MAZAK - INTEGREX 200 III ST	Chucking: to Ø200mm - Barwork: Ø65mm x 900mm max to sub-spindle chuck	8	YES	40	Sub Spindle - 2nd turret - Gantry Loader
DOOSAN - 3100ULY	Chucking: to Ø300mm Shaft work: Ø420mm x 3000mm between ctrs	5	YES	12	Work steady - HP Coolant
DOOSAN - Puma 480 XLM	Chucking: to Ø500mm Shaft work: Ø550mm x 3000mm between ctrs	4	NO	12	Work steady - HP Coolant
DOOSAN - 3100Y	Chucking: to Ø300mm Shaft work: Ø420mm x 1250mm between ctrs	5	YES	12	Work steady - HP Coolant
MAZAK - NEXUS 250M	Chucking: Ø250mm - Barwork: Ø77mm x 450mm	4	NO	12	Auto Barfeeder
MAZAK - NEXUS 200M	Chucking: Ø250mm - Barwork: Ø50mm x 450mm	4	NO	12	Gantry Loader

CNC 5-AXIS MILLING CENTRES

M/C Make - / Model	Max workpiece (prismatic parts)	Total Axes	Twin Pallet	Tool Stns	Other Features
MAZAK - Variaxis 630-5X MkII (#1)	Prismatic: 630mm x 630mm x 500mm height	5	YES	80	HP Coolant
MAZAK - Variaxis 630-5X MkII (#2)	Prismatic: 630mm x 630mm x 500mm height	8	YES	80	HP Coolant
DOOSAN - DNM350/5AX (#1)	Prismatic: 350mm x 350mm x 350mm height	5	NO	40	HP Coolant
DOOSAN - DNM350/5AX (#2)	Prismatic: 350mm x 350mm x 350mm height	5	NO	40	HP Coolant

CNC HORIZONTAL MILLING CENTRES

M/C Make - / Model	Max workpiece approx (prismatic parts)	Total Axes	Twin Pallet	Tool Stns	Other Features
MAZAK - HC NEXUS 6000-II	Prismatic: 900mm x 900mm x 1000mm height	4	YES	80	HP Coolant
MAZAK - HC NEXUS 4000-II	Prismatic: 630mm x 630mm x 650mm height	4	YES	40	HP Coolant
MATSUURA - H Plus 405	Prismatic: 800mm x 800mm x 800mm height	4	YES	80	HP Coolant

CNC VERTICAL MILLING CENTRES

M/C Make - / Model	Max workpiece approx (prismatic parts)	Total Axes	Rotary Table	Tool Stns	Other Features
MAZAK - Nexus V510C-II	Prismatic: 1000mm x 500mm x 500mm	3+1	YES	30	
MAZAK - VC SMART 530C (#1)	Prismatic: 1000mm x 400mm x 500mm	3+1	YES	30	
MAZAK - VC SMART 530C (#2)	Prismatic: 1000mm x 400mm x 500mm	3+1	YES	30	
BRIDGEPORT - VMC 1000 (#1)	Prismatic: 1000mm x 400mm x 600mm	3+2 *	YES *	30	* Rotary table has 2-axes
BRIDGEPORT - VMC 1000 (#2)	Prismatic: 1000mm x 400mm x 600mm	3+1	YES	30	
BRIDGEPORT - VMC 800	Prismatic: 800mm x 450mm x 500mm	3+1	YES	30	
BRIDGEPORT - VMC560	Prismatic: 560mm x 410mm x 500mm	3+1 *	YES *	20	* Rotary indexer
DAEWOO - Mynx 540	Prismatic: 1000mm x 500mm x 500mm	3+1	YES	30	
DAEWOO - Ace VC500	Prismatic: 500mm x 500mm x 500mm	3+1 *	YES *	30	* Rotary indexer - Twin Pallet

CNC TURNING CENTRES

M/C Make - / Model	Max workpiece (chucking / shaft work / barwork)	Total Axes	Work Stdy	Tool Stns	Other Features
DOOSAN - Puma LB (#1)	Chucking: to Ø300mm Shaft work: Ø320mm x 2000mm between ctrs	2	YES	12	HP Coolant
DOOSAN - Puma LB (#2)	Chucking: to Ø300mm Shaft work: Ø320mm x 2000mm between ctrs	2	YES	12	HP Coolant
DOOSAN - Puma SB	Chucking: to Ø300mm Shaft work: Ø320mm x 1000mm between ctrs	2	YES	12	HP Coolant
MAZAK - QT Smart 300	Chucking: to Ø250mm Shaft work: Ø250mm x 1275mm btwn ctrs Bar: to Ø80mm	2	YES	12	
HARDINGE - GT Conquest	Chucking: to Ø150mm x 200mm Barwork: Ø42mm x 150mm	2	NO	12	Auto Barfeeder
HARDINGE - T42 Super Prec'n	Barwork: Ø25mm x 50mm	2	NO	12	Auto Barfeeder
HAAS - TL1 (CNC Ctr Lathe)	Max Swing: Ø406mm Chucking: to Ø200mm x 800mm Barwork: Ø75mm x 250mm	2	YES	Manl	Thread re-cutting control

GRINDING
We have 4 Cylindrical Grinding machines allowing precision machining of parts up to 3000mm long